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HIGHWAY EARTHWORK AND PAVEMENT PRODUCTION RATES FOR CONSTRUCTION TIME ESTIMATION

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HIGHWAY EARTHWORK AND PAVEMENT PRODUCTION RATES FOR CONSTRUCTION TIME ESTIMATION

by

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To

my wife, Lichen Huang,

my daughter, Megan Kuo, and my son, Rick Kuo

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Highway Earthwork and Pavement Production Rates for Construction Time Estimation

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In recent decades, the complexity and size of highway construction projects have increased dramatically. Because of this change, Contract Time estimates for most construction projects have been based on the critical path method (CPM). However, with the use of the CPM, many problems associated with unrealistic contract timing are encountered. In order to solve these problems, many transportation agencies have attempted to establish a standard process to estimate Contract Time with the belief that reasonable Contract Time estimation should rely on realistic Production Rates.

Personal experience, historical records, and existing standards are usually used for Production Rates estimation. These sources are often unreliable because they do not include the effects of important drivers on Production Rates.

Many studies on construction productivity have been conducted. However, most of them focus on cost management rather than construction time estimation. Little information is available on Production Rates for construction time estimation.

This study is intended to be a reference tool for the highway construction industry to schedule and plan construction time. The purpose of this research study was to investigate the Production Rates of seven major Work Items in Earthwork- and Pavement-related construction. In addition, drivers that are known at the design stage and have a significant impact on Production Rates were identified and the effects of those drivers were quantified.

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CHAPTER I: INTRODUCTION

Construction projects have increased in both complexity and size in recent decades. This is in part, due to the pursuit of better construction efficiency and safety, lower construction cost, and higher quality (Gidado 1996). Because of this change, the more simplistic approaches of determining Contract Time using manual calculations and bar charts are not feasible. Instead, the critical path method (CPM) is usually employed. Consequently, today, an improved information system needs to be developed to support the application of CPM on Contract Time estimation.

1.1 RESEARCH BACKGROUND AND MOTIVATION

The critical path method (CPM) is a generally accepted method to estimate project duration for construction projects. Four steps are necessary to develop a CPM scheduling network for a construction project. First, a work breakdown structure is established to define the activities in the project. Second, the relationships between activities are then established. Third, the durations of the activities are estimated. Finally, the activities are compiled to develop a CPM scheduling network and the project duration is computed. Because project duration is calculated from compiling all activities into a scheduling network, the accuracy of estimating project duration is determined by the accuracy of estimating each activity-duration. The only way to obtain accurate activity duration is to use realistic Production Rates.

The duration of a construction project is usually determined by the clients at the design stage and is then documented in the bid documents. Contractors are usually under an obligation to evaluate the feasibility of the project duration before a contract has been awarded. In reality, however, time pressures typically do not allow contractors to perform this analysis. Further complicating the matter, clients frequently use inaccurate Production Rates to estimate construction time. Therefore, many projects are developed using unrealistic Contract Time duration.

Projects with overestimated project durations can cause unnecessary inconvenience to the traveling public and may reduce the project profits of the general contractors because of the increased project overhead. In addition these projects may allow contractors with lower productivity to bid, discourage the utilization of advanced techniques, or allow contractors to bid for additional work that otherwise they would not have been able to handle (NCHRP 1981; Herbsman and Ellis 1995).

Underestimation of project duration also leads to many problems (NCHRP 1981; Herbsman and Ellis 1995). Bid prices may be higher due to the increased cost of accelerated construction productivity. Construction quality may be reduced, and litigation may increase due to liquidated damages caused by project delay. Some qualified contractors may not even bid due to these concerns.

Using inaccurate Production Rates to estimate construction time has been recognized as a major source of bias in Contract Time estimation. To prevent inaccurate Contract Time estimation, a process for obtaining reliable Production Rate data is needed.

Recognizing this need, a reliable Production Rates database for construction time estimation will help the construction industry solve many problems associated with construction time. Clients may use the database to determine a reasonable Contract Time and also to apply it to site management. General contractors can use it to verify the Contract Time imposed on the bid documents and to monitor and manage the job.

The Center for Transportation Research (CTR) at the University of Texas, Austin, received funding from the Texas Department of Transportation (TxDOT) to develop a reliable Production Rate database for highway construction time estimation. This research project was undertaken by a research team comprised of research supervisor Dr. James T. O'Connor, who is a professor at the University of Texas Austin, and three graduate research assistants. The project was monitored by the Project Monitoring Committee (PMC) that included seven professional engineers at TxDOT.

1.2 RESEARCH OBJECTIVES

Many factors, such as weather conditions (Kahkonen 1991) and resource utilization (Proverbs et al. 1998) can cause large variances to Production Rates in highway construction. These factors can either speed up or slow down work production.

The main purpose of this study was to investigate and examine field construction Production Rates in two Work Areas, namely Earthwork and Pavement construction. Many studies have explored the relationship between productivity and various factors. The intention of this research was to identify the relationships between Production Rates and their drivers, with an emphasis on examining those drivers which have a great impact during the construction process and can be determined at the design stage. Further analysis will be carried out to determine the exact relationship and intensity of these relationships on the Production Rates.

The objectives of the research were to 1.) document Production Rate information for twenty-six major Work Items of highway construction projects from TxDOT's ongoing projects, 2.) identify the factors significantly influencing the Production Rate of each targeted Work Item and 3.) explore the relationships between daily Production Rates and identified Significant Drivers. A portion of the data from this TxDOT research project was used for the data analysis of this study.

1.3 Research Scope Limitations

Productivity can be viewed by management from two perspectives. The first perspective is for cost management purposes. This type of productivity is usually used to measure the efficiency of labor-intensive activities. The main purposes of such productivity measurement are to discover the factors which lead to low productivity, and to quantify their impacts on productivity for further improvements (AbouRizk et al. 2001; Christian and Hachey 1995).

The second perspective on productivity is for time management. This type of productivity is usually called Production Rate. The difference between the two types of productivity is discussed further in Chapter 2. This study will focus on the second type of productivity measurement and only concentrate on Production Rates associated with the major Work Items in highway Earthwork and Pavement construction.

1.4 Structure of Dissertation

This dissertation consists of eight chapters and twenty-six appendices which contain supporting information and results of the data collection and analysis. Chapter 2 elaborates on construction productivity with a comprehensive literature review. It begins with defining productivity and follows by focusing on quantification of the effects of factors on construction productivity, Earthwork and Pavement productivity, and the various methods used in analyzing construction productivity. Chapter 3 discusses the research methodology employed to achieve the research objectives. Chapter 3 starts with an overview of the research methodology, followed by a brief description of the preparation and execution of data collection. The chapter ends with proposed statistical methods used to analyze Production Rates and to identify the drivers of Production Rates.

Chapter 4 discusses the details of preparation and execution of data collection. At the beginning of this chapter, the research hypotheses of the study are introduced. Next follows a description of developing data collection tool, planning the data collection process and collecting the data. This chapter also summarizes the results of data collection. Chapter 5 presents the descriptive statistics of observed Production Rates. Chapter 6 presents the key findings of the hypotheses tests and the driver analyses for Earthwork-related Work Items. The relationships between Production Rates and their drivers are discussed in this Chapter. Similar to Chapter 6, Chapter 7 focuses on Pavement-related Work Items. Chapter 8 concludes this research study and provides suggestions for future research.

CHAPTER II: LITERATURE REVIEW

In order to estimate Contract Time of construction projects in a more consistent fashion, many transportation agencies have attempted to establish a standard procedure to determine Contract Time. Hancher et al. (1992) and Werkmeister et al. (2000) suggested further study on exploring realistic highway construction Production Rates. In addition the Transportation Research Board conducted studies in 1981 and 1995 to investigate the system used to determine Contract Time for construction projects in most state transportation agencies (NCHRP 1981; Herbsman et al. 1995). They indicated that "realistic Production Rates are the key in determining reasonable Contract Times" (Herbsman et al. 1995).

Productivity study has been an important and continuing area of interest in the construction industry. In this section, the definitions of construction productivity and Production Rates used in this study are presented. This chapter also reviews the methods for measuring productivity with different sources of Production Rates and the methods of quantifying the effects of factors on productivity. Furthermore, preceding productivity studies on Earthwork and Pavement construction, and methods of productivity analysis are presented.

2.1 DEFINITIONS OF PRODUCTIVITY

Productivity has been defined in many ways for different applications. Productivity can be defined using an economic model, project-specific model, or an activity model (see Equations 1, 2 and 3 below). Each of these models is measured for different purposes (Thomas et al. 1990).

Economic Model:

Productivity = Output $/Input $ (Equation 1)

Project-Specific Model:

Productivity = Square Feet/Dollars or Physical Output/Dollars

(Equation 2)

Activity Model:

Productivity = Output/Labor Cost or Output/Work Hours (Days)

(Equation 3)

In order to evaluate the impact of equipment technology on productivity, Goodrum and Hass (2002) modified the project-specific model to the partial factor model, as shown in Equation 4. They removed the material cost from the dollars in the project-specific model.

Partial Factor Model:

Productivity = Physical Output/(Labor Cost + Fixed Capital Cost)

(Equation 4)

The most popular definition of productivity is the unit rate (Borcherding et al. 1986) shown in Equation 5. The output is taken as the completed quantity, and the input is the engaged manpower to produce output. This definition is usually used for cost management to identify the variability of required manpower for completing a unit of output.

Unit Rate:

Productivity = Input / Output (Equation 5)

In this study, the activity model will be for Production Rates measurement. The duration of an activity is usually determined by multiplying the estimated Production Rates by the work quantity for an activity. Therefore, Production Rates used for construction time estimation will be measured as the completed quantity in a Work Area divided by the working days that a crew needs to complete an activity. The Work Area Quantity for each item is measured in the unit that is available for designers in order to facilitate the calculation of the activity duration. Table 2.1 indicates the units of measurement for the seven targeted Work Items.

Table 2.1 Definitions of Production Rates for the Targeted Work Items

Work Item	Unit of Measurement	Remark
Excavation	CY/Crew Day	CY: Bank Quantity
Embankment	CY/Crew Day	CY: Compacted Quantity
Lime-Treated Sub-grade	SY/Crew Day	SY: Completed Area
Aggregate Base Course	Lift-SY/Crew Day	Lift-SY: Total Area of Completed Working Lifts
Hot Mix Asphalt Pavement	TON/Crew Day	TON: Placed Weight
Slip-form Concrete Pavement	SY/Crew Day	SY: Completed Area
Conventional Form Concrete Pavement	SY/Crew Day	SY: Completed Area

2.2 APPROACHES FOR MEASURING PRODUCTIVITY

Various approaches such as work sampling (Liou and Borcherding 1986; Thomas 1991), the craftsman questionnaire (Chang and Borcherding 1986), and the foreman delay survey (Tucker et al. 1982) have been employed to investigate the causes that lead to inefficiency in construction tasks.

Work sampling has been utilized to evaluate workers' time utilization. Liou and Borcherding (1986) collected data from eleven nuclear power projects and four fossil fuel projects to study whether the unit rate productivity could be predicted using workers' time utilization data. This study concluded that there was a high correlation between them.

Thomas (1991) conducted a similar study to test whether a high direct work rate would lead to better labor productivity. It was reported that the direct work rate was not directly correlated with labor productivity. Winch and Carr (2001) also used work sampling to investigate what caused the difference in concrete productivity between France and the UK.

Chang and Borcherding (1986) used craftsman questionnaire sampling that combined a craftsman questionnaire and work sampling as a new approach to identify the sources of delays. This method provided some useful solutions to problems impacting construction productivity. This approach was tested at a large nuclear power plant site.

Tucker et al. (1982) developed a new approach, Foremen Delay Survey (FDS), to identify the sources of delay and to quantify time or dollar losses. This quantification method easily ranks the sources that caused delays according to their time and cost impacts. Subsequent application of the FDS on a job site can be used to evaluate the cost effectiveness of various solutions.

2.3 SOURCES OF PRODUCTION RATES

Developing scheduling networks is a complicated and time consuming task if there is not a reliable Production Rates resource. This is true even for an experienced project engineer (Kahkonen 1991). According to Hancher et al. (1992), in their review on Rowing's (1992) study, several resources are in current use. The participants of thirty-six Departments of Transportation (DOT) responded to a survey on resources used to estimate Production Rates for Contract Time determination. The results of the survey are shown in Figure 2.1. Forty-four percent of the respondents relied on personal experience to predict Production Rates. Thirty percent of the respondents used standard Production Rates and twenty-two percent used Production Rates from completed projects or historical records.

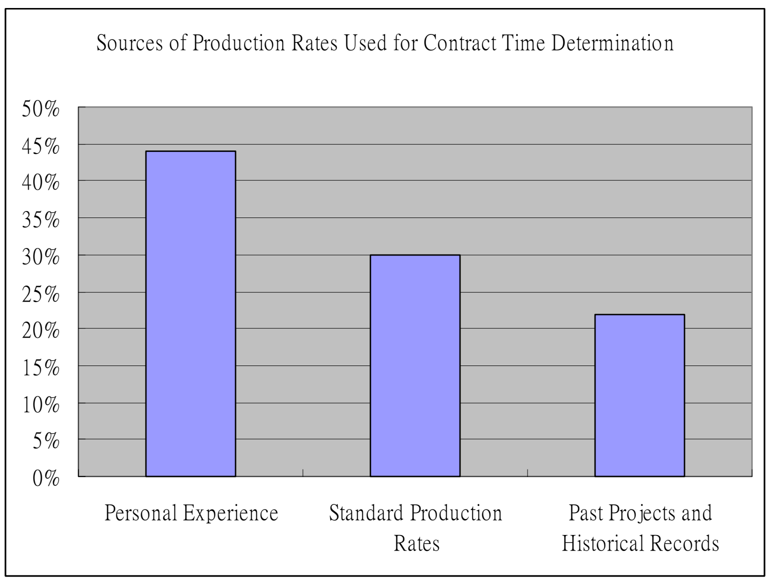


Figure 2.1 Sources of Production Rates Used for Contract Time Determination adopted from (Hancher et al. 1992)

The Production Rates obtained from personal experience and historical records were fragmented and unevaluated. Vital information such as the factors that significantly influence the variability of Production Rates was lacking. This resulted in that an average Production Rate was used as the representative

Production Rate for an entire project. The neglect of the effects of various factors caused Production Rates estimation to be inaccurate and biased.

Other sources of construction productivity are biased as well. The Construction Time Determination System (CTDS), a system developed by the Texas Department of Transportation (TxDOT) to guide designers in construction time estimation at the design stage, is inadequate as is the RS Means data. Although the RS Means Heavy Construction Cost Data publishes hourly and daily productivity and adjusts it regularly, those productivity data are intended primarily for cost management purposes.

2.3.1 RS Means

The productivity data in the RS Means Heavy Construction Cost Data is measured in both daily and hourly output formats. It is based on an eight hour working day during daylight hours and in moderate temperature. The rates have to be adjusted if hours in a working day total more than eight or when the environment is considered adverse. Unfortunately, no further information on the methods to adjust the productivity data is provided in RS Means. However, the productivity data in RS Means is primarily intended for cost management, therefore, its use in construction time estimation may be limited.

The differences between productivity for cost management and for construction time estimation is best demonstrated in the following example. For instance, an Operation for a 900 CY Excavation is performed by an excavator and three trucks within a day. A total of 7 hours will be spent on this Operation and within the 7 hours, 1 hour may be unproductive because the excavator breaks down. For cost management purposes, the productivity should be measured by the completed quantity of 900 CY plus the 6 hours of normal work, and the cost of the idle time should be counted as a project overhead. So, productivity is 150 CY/Hour and 1,200 CY/Day for an 8-hour working day for cost management purposes. But for the purpose of construction time estimation, the daily productivity is 900 CY/Day.

2.3.2 Contract Time Determination System (CTDS)

The Contract Time Determination System (CTDS) is "a conceptual estimating system for predicting Contract Time for highway construction projects and is not to be used for the detailed planning of actual construction activities for a project". (Hancher et al. 1992) This system is a product of research conducted by the Texas Transportation Institute and the Texas Department of Transportation (TxDOT) in 1992. A portion of this research was to explore Production Rates in highway construction. A survey was employed to investigate the daily Production Rate from twenty-five TxDOT districts. In the survey questionnaire, forty two Work Items were defined and the low, average and high Production Rates for each Work Item were asked to be estimated. From the forty three responses, the mean value of the low, average and high Production Rates for each item was computed. In addition, a request form was sent to all fifty state transportation agencies to request Production Rates data. Twenty-four states provided their Production Rates data for the study. Finally, a Production Rates database was developed using the two sets of results. Table 2.2 lists the finalized Production Rate of the CTDS study for the Work Items associated with the targeted items in this study. (The Work Items in this study are listed in Table 2.1.)

Table 2.2 Finalized Production Rates Database for CTDS

MAJOR WORK ITEMS	UNIT	LOW	AVERAGE	HIGH
Earth Excavation	CY	1,200	3,400	7,000
Embankment	CY	1,200	3,500	7,000
Lime-Treated Sub-grade	SY	2,000	4,000	6,000
Flexible Base Course	SY	1,500	3,000	4,500
Cement Treated Base	SY	1,500	3,000	4,500
Hot Mix Asphalt Base	Ton	500	1,200	4,500
Hot Mix Asphalt Surface	Ton	500	1,200	4,500
Concrete Paving	SY	1,000	3,000	5,000

Five factors, namely, *location*, *traffic conditions*, *complexity*, *soil conditions* and *quantity of work* were analyzed and their effects on Production Rates were investigated via a survey so that the Production Rates could be adjusted to fit job conditions in the CTDS study.

Table 2.3 displays the adjustment values for job factors for the eight related Work Items. Table 2.4 demonstrates the daily production base rates and the sensitivity factors determined from the surveys for the eight related Work Items in the CTDS study.

It was found that the eight related Work Items were very sensitive to quantity of work to be done according to the database in the CTDS. Earth Excavation, Embankment, Lime stabilization, and Cement-treated base material were all found to be influenced by soil conditions. Flexible base material, Hot mix asphalt base and Concrete paving were affected by location and Hot mix asphalt surface was affected by traffic.

Table 2.3 Adjustment Values for CTDS job Factors (Hancher et al. 1992)

Factors	Adjustment for Noted Conditions		
Location	Rural = 1.0	Small City = 0.85	Big City = 0.75
Traffic Condition	Light = 1.0	Moderate = 0.88	High = 0.70
Complexity	Low = 1.0	Medium = 0.85	High = 0.70
Soil Conditions	Good = 1.00	Fair = 0.85	Poor = 0.65
Quantity of Work	Large = 1.00	Medium = 0.88	Small = 0.75

Table 2.4 CTDS Base Production Rates and Sensitivity Factors (Hancher et al. 1992)

MAJOR WORK ITEMS	UNIT	DAILY PRODUCTION BASE RATE	Sensitivity Factors
Earth Excavation	CY	4,200	l t c S Q
Embankment	CY	4,200	l t c S Q
Lime Stablization	SY	4,500	l t c S Q
Flexible Base Material	SY	3,400	L t c s Q
Cement Treated Base Material	SY	3,400	l t c S Q
Hot Mix Asphalt Base	Ton	1,400	L t c s Q
Hot Mix Asphalt Surface	Ton	1,400	l T c s Q
Concrete Paving	SY	3,400	L t c s Q

L: Location; T: Traffic; C: Complexity; S: Soil Condition; Q: Quantity of Work

*Sensitivity Factors with capital letters indicate significant factors for individual work item

2.3.3 Historical Records

For this study, some highway construction Production Rates data were collected from historical data recorded by contractors and were compared with observed Production Rates data. Most collected historical data were only available for Excavation, Embankment and Hot mix asphalt pavement. There was not sufficient information in these historical records to identify the factors that cause variability in daily Production Rates. Even for other Work Items such as Lime-treated sub-grade, Aggregate base course, Slip-form concrete pavement, and Conventional form concrete pavement, rates for some sub-activities such as remixing Lime-treated sub-grade, processing Flexible base, installing rebar for Concrete pavement, were not documented in the historical records.

2.4 GENERAL FACTORS AFFECTING PRODUCTIVITY

Many productivity studies have identified productivity factors and measured their effects on productivity. Most of these were interested in the identification and quantification of factors that caused losses of construction productivity. Frequently cited factors from these studies include weather, scheduled overtime, disruption, congestion, and region (Halligan 1994; Koehn 2001). This section will review published studies associated with the identification and quantification of productivity factors related to this study.

Thomas and Yiakoumis (1987) employed the factor model to present relationships between labor productivity and productivity factors. The factor model displays the effects of learning curve and other factors on labor productivity, as shown in Figure 2.2. In the factor model, the ideal productivity curve presents a correlation between the cumulative man-hour per unit of work and the cumulative unit of work in an ideal condition of no disruption. The ideal productivity curve is varied with different crews. Their study indicated that losses in productivity are caused by numerous factors such as environmental factors, site factors, management factors, and design factors.

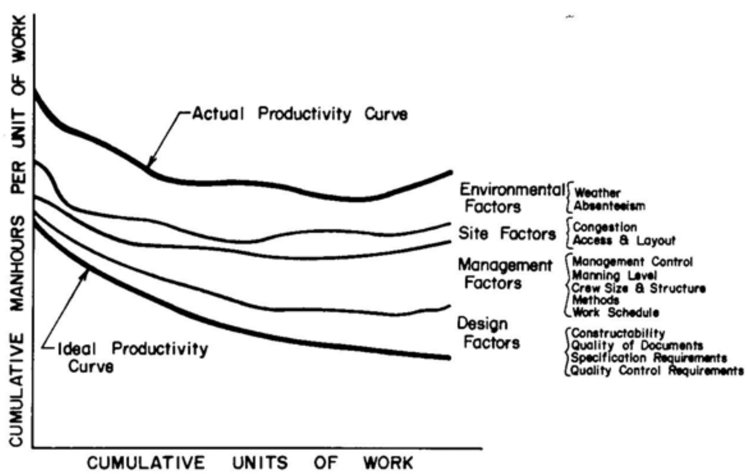


Figure 2.2 Factor Model (adopted from Thomas and Yiakoumis 1987)

2.4.1 Weather

Weather conditions at the construction site have a large impact on highway construction. Almost half of construction Operations are sensitive to weather conditions (Oglesby et al. 1989). Precipitation, extremes of temperature, and humidity cause productivity loss (Borcherding 1991; Halligan 1994) and may even cause activities to be delayed. Hot temperature may increase the frequency of travel time for the workers in order to avoid heat and as such, productive time may be reduced as a result (Borcherding 1991). Cold temperature may increase the idle time of workers standing beside heat sources to warm themselves up (Borcherding 1991). Weather also has a huge impact on some work Operations, such as Lime-treated sub-grade, Concrete placement and Hot mix asphalt, as these Operations cannot be carried out in extreme weather (TxDOT 1993).

Several studies have been conducted to quantify the effects of adverse weather on labor productivity. Grimm and Wagner (1974) conducted a study to measure the effects of temperature and humidity on masonry productivity. In their study, other factors influencing the loss of productivity were controlled to be constants in order to find the effects of temperature and humidity on labor productivity. It was reported that masonry productivity decreased with increasing deviation from 75 degrees of Fahrenheit or humidity of 60%.

An experimental study (NECA 1974) conducted by the National Electrical Contractors Association measured the labor productivity of an electrician installing duplex receptacles in an environmental chamber where temperature and humidity was controlled. It was found that productivity decreased when the temperature was above 80°F and below 40°F, or when the relative humidity was above 80%. Another study examined losses of labor productivity on steel erection due to cold temperature. It found that labor productivity was impacted by 32% due to cold temperature (Thomas et al. 1999).

2.4.2 Scheduled Overtime

Scheduled overtime refers to “a planned decision by project management to accelerate the progress of the work by scheduling more than 40 work hours per week for an extended period of time for much of the craft work force” (Thomas and Raynar 1999). Scheduled overtime causes fatigue among workers and reduces motivation and indirectly causes labor productivity to deteriorate. Many studies have attempted to quantify the effects of such overtime on labor productivity. The 1980 Business Roundtable republished the findings of weekly productive returns from working 50 or 60 hours a week for various numbers of weeks. In the late 1960s, Weldon McGlaun reported these findings to members of the National Constructors Association. It was found that productivity during the first week of scheduled overtime fell dramatically and that productivity continued to go down week by week. After working for 50 hours per week continuously for seven weeks, the weekly output was similar to that when the workers actually worked 40 hours per week. For a 60 work-hour week, by the ninth week of scheduled overtime, the weekly output was similar to the output of working for only 40 hours a week. This is clearly shown in Figure 2.3.

However, conclusions from a study conducted by the Construction Industry Institute (1988) were inconsistent with previous findings. This study concluded that "productivity does not necessarily decrease with an overtime schedule" based on monitoring 25 crews on seven projects (three insulation crews, seven pipe crews, eleven electrical crews, one formwork crew, one rebar crew, and two concrete crews).

Thomas and Raynar (1997) quantified the effects of scheduled overtime on productivity by studying the productivity of electrical and piping craftsmen on four active construction projects. Their study reported a loss of 10% ~ 15% efficiency for both scheduled overtime scenarios of 50 working hours and 60 working hours per week.

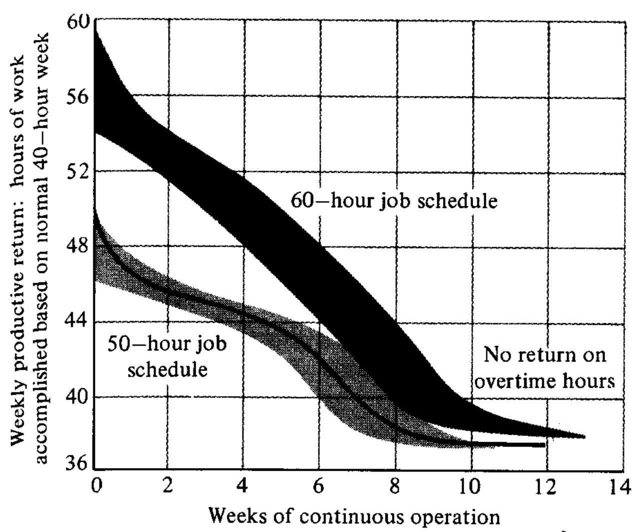


Figure 2.3 Effective return from working 50 or 60 hours a week for various numbers of weeks (Source: Business Roundtable Cost Effectiveness Study Report C-3, November 1980.)

2.4.3 Disruptions

Disruptions are considered to have a huge impact on construction productivity. Disruptions can be divided into two categories: short term disruptions, and long term disruptions. A short term disruption leads to productivity loss as extra work is needed to overcome obstacles causing disruptions. A long term disruption may even eradicate the productivity increases from learning curve effects (Halligan 1994).

Thomas and Raynar (1997) classified disruptions into three categories, which are listed as follows:

1. Resources
   - Material availability
   - Tool availability
   - Equipment availability
   - Information availability
2. Rework
   - Change
   - Rework
3. Management
   - Congestion
   - Out-of-sequence work
   - Supervisory

- Miscellaneous

In their study, each type of disruption was measured by frequency of occurrence during a working week. It was found that more working days per week were required when there was a higher frequency of disruption. Rework, tool availability, material availability, equipment availability, and congestion were found to have significant impact on performance.

2.4.4 Congestion and Accessibility

Ovararin and Popescu (2001) conducted a study to quantify the effects of sixteen field factors on productivity loss in masonry construction. Fifty participants who were either owners or the chief estimators of the masonry contractors were randomly selected and a survey package was distributed to them.

In their study, productivity losses due to levels of congestion and accessibility were quantified. The definition of levels of congestion and accessibility are shown in Table 2.5. The disruptions of an additional crew working in the same area were evaluated as the field condition on levels of congestion. The results reported that congestion caused 10 to 32 percent productivity loss. Levels of accessibility were evaluated by considering the convenience of accessing the Work Area and the distance between the Work Area and material storage. They found that disruptions associated with accessibility caused 13 to 35 percent productivity loss.

Table 2.5 Definition of Congestion and Accessibility (Ovararin and Popescu 2001)

Field Factors	Standard Field Conditions		
	Minor	Moderate	High
Congestion	An additional crew/contractor working in the same area 1 day/week	Additional crews/contractors working in the same area 2~3 days/week	Additional crews/contractors working in the same area everyday
Accessibility	4 days/week, < 25 yards to materials storage	2~3 days/week, 25~50 yards to materials storage	Once/week, > 50 yards to materials storage

2.4.5 Region

The location of a construction project was found to be a factor influencing construction Production Rates. A productivity study was conducted by Koehn in 2001 to investigate the Production Rates in different regions in Bangladesh. Low production was found in rural areas. According to their investigation, lack of training and improper supervision was the major reasons for low production. Most big construction companies in Bangladesh are located in urban areas and only big construction companies provide training for the operation of sophisticated equipment.

Moreover, low productivity can be due to workers' fatigue from long distance commuting (Borcherding and Alarcon 1991). The location of a project can affect both workers' motivation and the availability of advanced tools or equipment. Project location can also have an impact on the availability of skilled labor (AbouRizk et al. 2001). Worker motivation (Borcherding 1980;

Borcherding and Garner 1981) and the availability of skilled labor (Koehn and Brown 1985) have a huge impact on construction productivity.

2.4.6 Learning curve

When performing repetitive tasks, productivity tends to increase as the number of cycles increase. This increased productivity is due to experience gained from previous tasks, improved resource allocation, better engineering support, better management and supervisions, and development of more efficient methods (Thomas et al. 1986). Thomas et al. (1986) conducted a study to evaluate the efficiency of various learning curve models on productivity estimation and to investigate the learning rates from four field studies. The learning rate is the rate of change of the cumulative average man-hours when production doubles. It was found that the learning rate was not constant and therefore a straight line model is not appropriate. Instead, the cubic power model was found to be the best learning curve model among five studied models.

2.4.7 Other factors

Sanders and Thomas (1991 and 1993) conducted a series of research studies related to masonry productivity. The purpose of their 1991 study was to identify the major project-related factors that significantly influenced masonry productivity. They used ANOVA to examine whether the average masonry productivity in each category was statistically different for each of the factors associated with masonry productivity. This study indicated that four of the investigated factors had significant impacts on masonry productivity: work type, building element, construction methods, and design requirements. In their 1993 study, a masonry prediction model was developed to estimate the masonry productivity based on different crew sizes as well as those factors identified in their 1991 study. This model was established by using the multiple regression analysis. The R square of their model was 0.411.

2.5 PRODUCTIVITY STUDIES OF EARTHWORK AND PAVEMENT

2.5.1 Earthmoving Production Rates and Match Factor

The maximum possible Production Rate of an Excavation Operation is equivalent to the maximum Production Rate of the loading machine (Gransberg 1996; Smith 1999). This rate can only be achieved under ideal conditions with a sufficient number of trucks to allow the loading machine to maintain its maximum productivity. In reality, this condition seldom occurs due to concerns regarding cost-effectiveness of trucking and traffic conditions.

Many studies have been conducted to estimate the Production Rate of Excavation Operations (Gransberg 1996; Peurifoy and Schexnayder 2002). The rates were determined based on the characteristics and numbers of loading machines and haul trucks, and characteristics of the haul road and excavated materials. An example Production Rate calculation for an Excavation Operation is described in the following paragraph (Peurifoy and Schexnayder 2002).

In this example, a loader is assumed to be used for the Excavation Operation. The loader cycle time is calculated according to the speed of a loading machine and the capacity of a truck. The truck cycle time is computed depending on the loading speed, traveling speed and unloading speed. Furthermore, the optimum number of trucks required for the Excavation Operation is calculated by dividing the truck cycle time by the loading cycle time. The optimum number is usually not an integer value. Therefore, the two integer values that are closest to the optimum number are established as the possible number of trucks for further Production Rate and unit cost analysis. If the number of trucks is more than the optimum value, the Production Rate of an Excavation Operation will be equivalent to the Production Rate of the loading machine, and is computed as shown in Equation 6. If the determined number of trucks is less than the optimum value, the Production Rate of an Excavation Operation will be equivalent to the Production Rate of the truck fleet, and is computed in Equation 7.

$$\textbf{Production Rate (lcy/hr) = Truck load (lcy)} \times \frac{\textbf{60min}}{\textbf{Loader cycle time (min)}}$$

(Equation 6)

$$\textbf{Production Rate (lcy/hr)} = \textbf{Truck load (lcy)} \times \textbf{Number of Trucks} \times \frac{\textbf{60min}}{\textbf{Truck cycle time (min)}} \qquad \text{(Equation 7)}$$

Smith (1999) established a multiple regression model, with the R square of 90.6%, to predict earthmoving productivity. Four highway construction projects were involved in the study. From these four projects, a total of 141 earthmoving Operations were observed and analyzed. The factors included in the regression model were only the variables which could be determined or estimated in advance of earthmoving Operations. Six factors were identified as the major drivers from their earthmoving productivity model: number of trucks, number of buckets per load, volume per bucket, one-way haul length, match factor and travel time.

The match factor (MF), as shown in Equation 8, is used to measure if there are sufficient haul units to reach the possible maximum Production Rate of an Excavation Operation. If the MF is greater than one, the possible maximum Production Rate of an Excavation Operation is equivalent to the maximum Production Rate of the loading machine. If the match factor is less than one, the possible maximum Production Rate is equivalent to the multiplication of the maximum Production Rate of the loading machine and the match factor.

$$\textbf{MF} = \frac{\textbf{Number of Haulers} \times \textbf{Loader Cycle Time}}{\textbf{Number of Loaders} \times \textbf{Hauler Cycle Time}} \qquad \text{(Equation 8)}$$

2.5.2 Truck Payload

The truck payload is computed as the multiplication of the number of buckets per load and the volume per bucket. Schexnayder et al. (1999) conducted a study on the effect of truck payload weight on earthmoving productivity. The production of trucks was tracked for different haul distances and varying loading weights. It was found that the production of earthmoving increased with an increase in average payload of haul trucks but decreased when the average payload exceeded the rated gravimetric capacity.

2.5.3 Rainfall

Rainfall has a great impact on highway construction productivity. El-Rays (2001) presented a decision support system that could quantify the impact of rainfall on productive day losses and estimate the duration for certain types of construction Operations in highway construction projects. A knowledge base of the effects of rainfall on productive day losses was acquired from interviews with experts in the highway construction industry. The experts indicated that three factors, namely the types of construction Operations, the intensity of rainfall and the drying conditions on site, are highly correlated to rainfall-related productivity losses. In addition they indicated that earthmoving, construction of the base course, construction of drainage layers and paving construction are the four tasks in highway construction that are most sensitive to rainfall (El-Rays and Moselhi 2001).

2.5.4 Advance of Technology

Technology advancements lead to improvement of construction productivity due to level of control, amplification of human energy, and information processing (Schexnayder and David 2002). Bhurisith and Touran (2002) conducted a case study with regard to obsolescence and equipment Production Rate. The ideal Production Rates of wheel-type loaders, track-type loaders, scrapers and crawler dozers were collected from the 1983, 1992 and 1998 *Caterpillar Performance Handbooks*. Production Rate changes according to change of technology were also examined. The results showed that Production Rates under ideal conditions have increased 1.58% on average per year due to technology advancements.

Jonason et al. (2002) studied the productivity of Earthwork for different types of advanced positioning systems. In their study, the productivity of Earthwork for each advanced positioning system was estimated based upon site observation and interviews with field personnel. It was found that advanced positioning systems lead to improvements on schedule and cost performance of Earthwork construction due to saving time and reducing the cost of field surveying. However, there are still several shortcomings that inhibit the usage of these advanced positioning systems. The application of 2D and 3D guidance technologies are limited to Work Areas with direct line-of-sight between the control station and the receiver on the equipment. Furthermore, GPS-related signal noise can affect the accuracy of measurement.

Goodrum and Hass (2002) studied the change of productivity and technology according to productivity data published by RS Means, Richardson, and Dodge between 1976 and 1998. They found a substantial improvement in partial factor productivity among activities that have had significant improvements according to a technology index. The technology index was evaluated as a function of level of control, amplification of human energy, information processing, functional range, and ergonomics of equipment. It was found that site work has had the greatest improvement in mean partial factor productivity and technology index when compared to other work activities.

Allmon et al. (2000) examined changes in construction productivity and unit cost for twenty Work Items according to productivity data published by RS Means between 1974 and 1996. It was found that the productivity of soil compaction and concrete placement increased by 260% and 55%, respectively. It was reported that new technology was the main driver of this improvement.

2.5.5 Traffic

Jiang (2003) studied the effects of traffic flow on the construction productivity of Hot mix asphalt pavement. He observed 24-hour traffic flow at a cross-over Work Zone and used queuing theory to compute the cycle time of transporting trucks in a hypothetical Hot mix asphalt Operation. According to the cycle time and an assumed number of transporting trucks, construction productivity of Hot mix asphalt pavement was computed. It was found that traffic delays increased the cycle time of transporting trucks. As a result of increasing cycle time, the construction productivity, in terms of tonnage per hour, decreased. However, adding more transport trucks could balance the negative effects of congested traffic flow.

2.5.6 Construction Productivity Associated with Concrete Pavement

A constructability analysis tool was developed by Lee et al. (2000) to help the California Department of Transportation to examine the productivity performance and the traffic impacts of several strategies used on concrete pavement rehabilitation and construction in an urban area. A hypothetical concrete pavement construction (including the demolition of existing concrete pavement and base course, construction of Cement-treated base and construction of concrete pavement) was used to examine the variability of productivity performance with the variability of design profile, required curing time, working methods, paving strategies, truck capacity, and loading/discharging time. This hypothetical project involved the replacement of two outer lanes of a four-lane roadway during weekend closures from 10:00 p.m. Friday to 5:00 a.m. Monday. The process of pavement rehabilitation, lead-lag relationships between activities, constraints that limit construction productivity, approximate process productivity, and capacities of equipments and facilities were gathered based on the previous urban freeway rehabilitation experience of a group of experienced California concrete paving contractors.

Table 2.6 presents their findings in terms of percent reduction in ideal productivity (lane-km/a weekend closure) for different factors. Slab thickness was found to have the greatest impact on the productivity of concrete pavement rehabilitation because thicker slabs increase the quantity of demolition. The curing time of poured concrete varied with the usage of various types of concrete material. Because the construction time was limited to 55 working hours in a weekend closure and the constructed lanes had to open for traffic at the end of closure, more curing time lead to less construction time and output. The work method (that reflects the relative sequence of base construction and paving construction) also had a great impact on output. In addition, the paving lane (which refers to the working sequence of the two replaced lanes) and the end dump truck capacity and load/discharge time also had impacts on output.

Table 2.6 Percent Reduction in Production Capacity under Optimistic Conditions (adopted from Lee et al. 2000)

Options		Comparison	Reduction
Design Profile		203mm --> 254mm	40%
		203mm --> 305mm	47%
		254mm --> 305mm	12%
Curing Time		4 hours --> 8 hours	10%
		8 hours --> 12 hours	11%
		4 hours --> 12 hours	19%
Working Method	203-mm slab	Concurrent --> Sequential	29%
	254-or 305-mm slab	Concurrent --> Sequential	21%
Paving Lane	203-mm slab	Double --> Single	17%
	254-or 305-mm slab	Double --> Single	7%
End Dump Truck Capacity		22 Ton --> 15 Ton	15%
Load/Discharge Time		3 Minutes --> 4 Minutes	24%

2.6 METHODS OF PRODUCTIVITY ANALYSIS

Expert Systems are another technique to deal with relationships between productivity and driving factors. Hendrickson et al. (1987) developed an expert system to predict the activity duration for masonry construction. The productivity estimation, as a part of the activity duration estimation, included two steps. The first step was to estimate the maximum expected productivity and a subsequent step was to adjust the maximum rate to a reasonable rate according to the characteristics of the job or site. The information associated with productivity was established based on interviews with an experienced mason and a supporting laborer. Another Expert System was developed by Christian and Hachey (1995) to estimate the Production Rate of concrete pouring. After a simple question-and-answer routine, the Expert System was able to estimate Production Rates of concrete pouring, depending on established decision rules.

In addition, Neural Networks have been used by many researchers (Karshenas and Feng 1992; Lu et al. 2000; AbouRizk et al. 2001) to predict construction productivity. A Neural Network has the capability of learning with an increase in data. The greatest advantage of using Neural Networks to predict construction productivity is that it can include interactive effects of multiple factors in the productivity estimation if the network is trained using an adequate and representative data set. In reality, the size and quality of the training data set usually limits the effectiveness of Neural Networks due to lack of standards for collecting real productivity data.

2.7 ADVANCING TO PRESENT RESEARCH

Although many studies have addressed construction productivity, few studies have been undertaken to study Production Rates for highway construction time estimation. The purpose of this study is to examine and determine the Production Rate in two Work Areas, namely Earthwork and Pavement construction for highway projects. Such information will help the Texas Department of Transportation (TxDOT) to improve the accuracy of highway construction time estimation and should lead to better project time management.

CHAPTER III: RESEARCH METHODOLOGY

3.1 OVERVIEW OF RESEARCH METHODOLOGY

Figure 3.1 provides an overview of the research methodology. The research objectives and scope were determined first. A survey was conducted to select critical Work Items for the study while a comprehensive literature review helped in understanding relevant productivity factors and productivity measurement methods. A data collection process and associated tools were developed, incorporating selected factors and methods. Data associated with Production Rates were collected and analyzed. Conclusions and recommendations were developed.

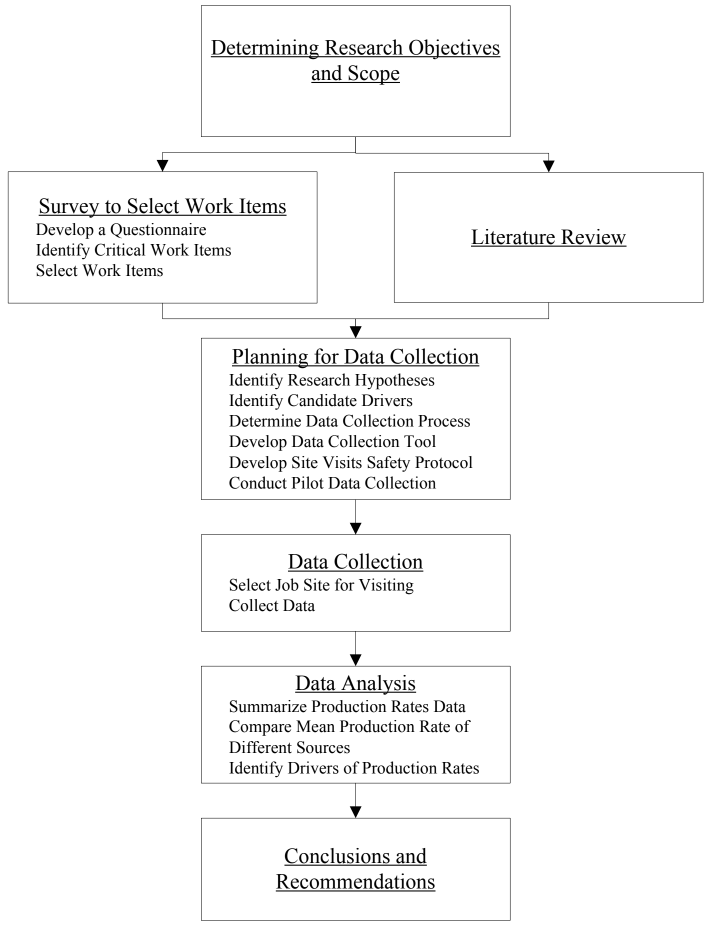


Figure 3.1 Research Methodology

3.2 Research Formulation

The research objective is to develop improved information on Production Rates for highway Earthwork and Pavement construction so that Contract Time estimation can be enhanced. Production Rates as well as relevant factors were collected from a selection of TxDOT's on-going highway construction projects. Drivers of Production Rates for each Work Item were explored through statistical analyses and their relationships with Production Rates were further quantified. In addition, CTDS Production Rates were compared with the field-collected rates to examine the differences.

3.3 SURVEY TO SELECT TARGETED WORK ITEMS

A highway construction project usually includes hundreds of Work Items. Some of them are more critical to project schedule than others. A survey questionnaire, as shown in Appendix A, was used to identify the priority of Work Items in this study. The survey questionnaire includes a Work Item list, adapted from the TxDOT's Contract Time Determination System (CTDS), and the binary question (Yes or No) of tracking requirements for each Work Item. The Work Item list in the CTDS is a comprehensive list (Hancher et al. 1992) of Work Items for highway construction projects and it includes all major Work Items from the thirteen types of TxDOT construction projects.

Survey participants were selected by the Project Monitoring Committee (PMC) of TxDOT research project 0-4416. The survey questionnaire was distributed to thirteen TxDOT engineers working in the Design and Construction divisions. The results of the survey are presented in Appendix B. Twenty five Work Items were indicated by more than seven engineers as the Work Items that should be tracked. Eight of these belong to Earthwork and Pavement construction. The results were presented and discussed in a PMC meeting. Consequently, seven Work Items related to Earthwork and Pavement construction were established as priorities for this study. These include Excavation, Embankment, Lime-treated sub-grade, Aggregate base course, Hot mix asphalt pavement, Slip-form concrete pavement, and Conventional-form concrete pavement.

3.4 PLANNING FOR DATA COLLECTION

A data collection process plan was developed in order to ensure the effectiveness and efficiency of data collection. Following that, data collection tools were developed. These tools include a project-level data collection tool (Appendix C), a Work Zone- and Work Item- level data collection tool (Appendix D), and individual Work Item sheets (Appendix E). The project-level data collection tool was used to collect general information on selected projects. The Work Zone- and Work Item-level data collection tool was used to document specific information regarding Work Items and Work Zone at the investigated site. Work Item sheets were developed for each targeted Work Item and were used as a guideline to ensure thoroughness and consistency in the data collection process. They were also used to collect information on specific Production Rate Factors. In addition, a site visit safety protocol (Appendix F) was developed to ensure safety during the data collection process.

Upon finalization of the data process and tools, a pilot data collection effort was carried out in order to test the process and tools. Further adjustments to the process and tools were made to improve the effectiveness of data collection.

3.4.1 Data Collection Process

A data collection process plan, shown in Figure 3.2, was developed to enhance the effectiveness of collecting data. Three cycles were included in this plan. The first consists of the process flows of conducting a district meeting to select projects for data collection, the second involves conducting a project meeting to kickoff the data collection in a project and third, the regular collection of project data at the construction site.

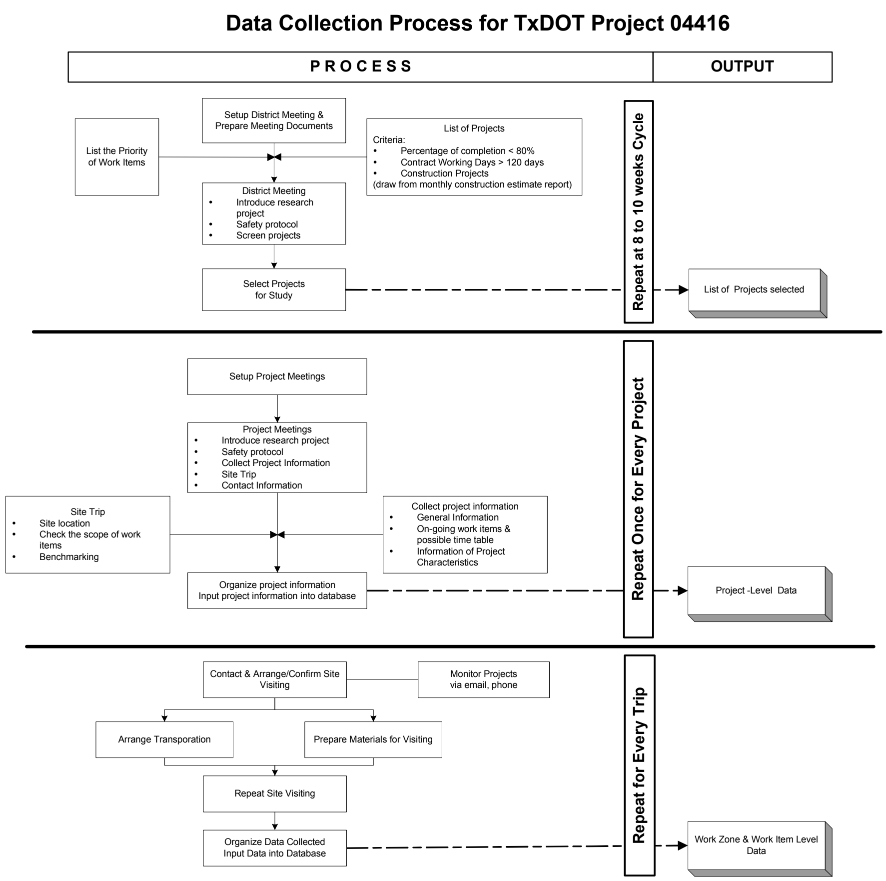


Figure 3.2 Data Collection Process

3.4.1.1 Selecting Job Sites for Data Collection

The first cycle in Figure 3.2 displays tasks associated with the district kickoff meeting. District meetings were conducted at an interval of every eight to ten weeks. Two important meeting tasks included the introduction of the research to the district construction engineer and engineers from area offices, and obtaining input for selecting appropriate projects for data collection. In addition, the research team was required to obtained permission and further guidance on collecting data and confirmed safety procedures.

The information of on-going projects were reviewed from the construction report – highways and construction monthly estimate report on the TxDOT web site (http://www. dot. state. tx. us/business/projectreports. htm). Projects which were less than 80% complete and that had a contract project duration greater than 120 working days were listed for the further screening at the district meeting. Projects with serious delays due to legal problems or change orders were eliminated as any Production Rates collected would likely be outliers.

3.4.1.2 Project Meetings

Project meetings were conducted following a district meeting to achieve three objectives. First, the purpose of the research was introduced to site personnel to facilitate data collection. An introduction of the research project was presented at the beginning of the project meetings to obtain the assistance from the TxDOT site personnel and to prevent redundant or incorrect information from being collected. Secondly, detailed information regarding selected Work Items and their respective work schedules were obtained. Thirdly, general information on the targeted projects was collected and work progress status was benchmarked. Sources of project information included project contracts, project drawings, and some project manager opinions.

3.4.1.3 Regular Visits

The research team visited the selected job sites on a regular basis to benchmark and collect data after the project meeting. Instead of stop-watch type observations, discrete observations were employed to collect data. The first step of discrete observation was to "benchmark" the initial status of targeted activities. The location and progress of a targeted activity were documented and characteristics of the Work Zone were evaluated. Work quantity completed-to-date and crew and machinery information pertaining to the elapsed period between the first benchmarking/last observation and current observation were documented along with any disruptions and the number of working days. The production quantities were collected from the TxDOT diary and/or, site management or contractor reported quantities that had been approved by TxDOT personnel. Working day and disruption information were collected from interviews with TxDOT personnel. The time interval between two observations ranged from one to two weeks. At the end of each regular visit, new data points were computed. Subsequent observations were carried out as necessary.

3.5 DATA COLLECTION

A total of seven TxDOT districts, as shown in Table 3.1, were selected to collect Production Rate data for this study. The state was divided into four areas according to weather and terrain, and up to three districts were selected from each of these four areas to avoid bias caused by weather and region. Two to six projects in each district were observed simultaneously for a period of two to three months.

Table 3.1 Selected Districts vs. Area

Districts	Area of Texas
D1	Central and South Texas
D2	Coastal
D3	Central and South Texas
D4	North Texas
D5	Coastal
D6	Panhandle and West Texas
D7	Central and South Texas

To ensure consistency in the tracking of working days, a rational for Production Rate computation was determined by the research team and TxDOT's Project Monitoring Committee (PMC) members and is displayed in Table 3.2. If there was a delay effect of not greater than two hours in a 10 working-hour day and the delay was caused by weather, unworkable soil conditions, traffic accident, construction accident, equipment down time, unavailability of material, trade problem or absenteeism, the day was counted as a working day. If the delay effect was greater than two hours but less than half a day, the day was counted as a half working day. If the delay effect was more than half a day, it was considered as a non-working day. For Lime-treated sub-grade, if a 1st curing occurred on Holidays, Non-working days, Non-working weekends, and Off-day, the days were added to total working days when the duration was not greater than 2 days. Thus, the maximum total duration of 1st curing was limited to 2 days if Holidays, Non-working days, Non-working weekends, and Off-day were counted. For delays caused by Right of way, Unforeseen conditions, or Instructions from TxDOT's engineers, delays were not counted as working days. Also, total working days were adjusted if overtime was more than two hours per day.

Table 3.2 Rational for Production Rate Computation

Factors	**No Adjustment** *Effect Embedded in the Production Rate*	**Corrected** *Effect isolated or adjusted*
Weather (Rain, Too Wet, Snow, Wind etc) Unworkable Soil Conditions Traffic Accident Construction Accident Equipment Down Time Material Unavailable Trade Problem Absenteeism	✓ *If Delay Effect < ½ Day*	✓ *If Delay Effect >= ½ Day*
Holidays, Non-Working Day, Non-Working Weekend, Off-Day	✓ *If Number of Days of 1st Curing <= 2 Days* *#260 Lime Treated Subgrade 1^{st} Curing only*	✓
Regional shortage (ROW, Unforeseen Condition, TxDOT Direction)		✓
Overtime		

3.6 DATA ANALYSIS

3.6.1 Descriptive Statistics and Box Plots

Descriptive statistics were often employed to summarize data such as mean, sum, counts, and frequency of variables. In this research, data are shown on scatter plots to demonstrate relationships or associations between two variables. Relationships may be observed with non-random scatter in such plots.

A box plot is a statistical summary that presents mean, median, quartile, outliers and extreme values in a graphical format. Figure 3.3 is an annotated sketch of a box plot (SPSS Base 10.0 Applications Guide). The horizontal line in the shaded box represents the median or 50th percentile of the plotted sample.

The dark circle highlights the mean of the targeted sample. The top and bottom end of the box represents the 3rd and 1st quartile of the sample respectively. The length of the box, from 1st quartile to 3rd quartile, denotes the inter-quartile range (IQR). The horizontal line between 3rd quartile and 3rd quartile + 1.5 * IQR and between 1st quartile and 1st quartile – 1.5 * IQR are the highest and lowest observed values respectively, excluding outliers in the sample. Points beyond the (3rd quartile + 1.5 * IQR) and under the (3rd quartile + 3 * IQR) as well as points under the (1st quartile – 1.5 * IQR) and beyond (1st quartile – 3 * IQR) are outliers. Points beyond these outer limits are considered extreme values.

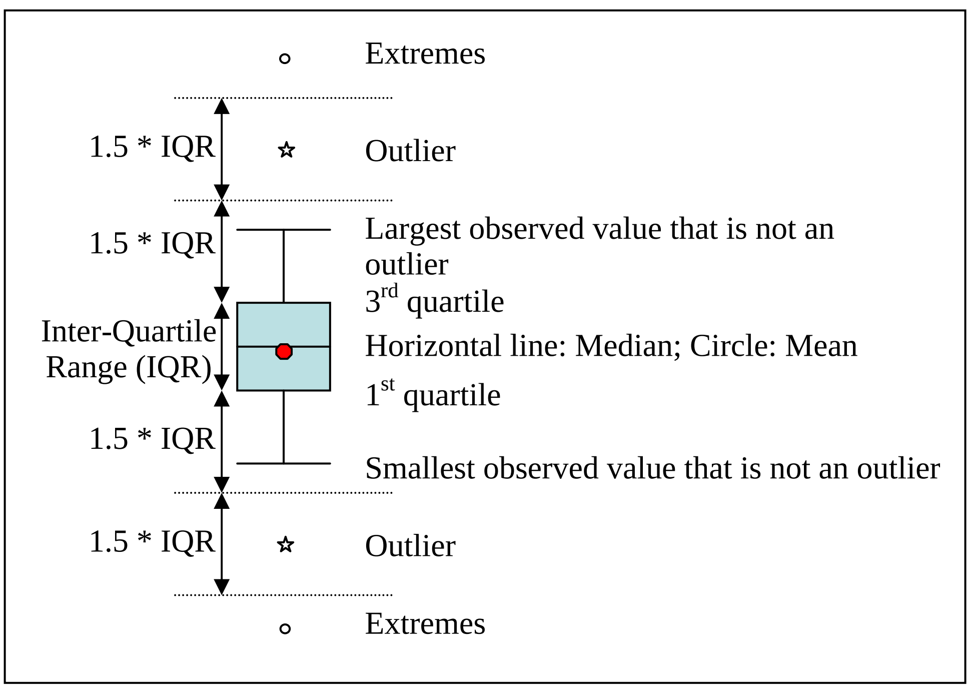


Figure 3.3 Annotated Sketch of the Box Plot

Side-by side box plots were used to compare the Production Rates of the observed data, CTDS, and historical records. Table 3.3 shows an overview of historical records utilized by this study. These were collected from three districts in Texas, namely D3, D4 and D8. Both D3 and D4 districts were also involved in the Production Rates observations. The historical records collected from these two districts were gathered from on-going projects. Production Rate information was retrieved from daily logs and payment management systems of the general contractors. The historical records from D8 were collected from quantity and working-day records in their schedule network of eleven completed projects.

Table 3.3 General Information of the Sources of Historical Records

District	Project ID	Number of Project	Progress Status of Records
D3	As-Built 1	1	Start ~ 62%
	As-Built 2	1	Start ~ 60%
D4	As-Built 3	1	Start ~ 34%
	As-Built 4	1	Start ~ 29%
D8	As-Built 5	1	Start ~ End
	As-Built 6	1	Start ~ End
	Other As-Builts	9	Start ~ End

3.6.2 Test of the Difference of Mean Observed Production Rates and Average CTDS Production Rates

Because little information of original data is available to determine the distribution of the Production Rate data in the CTDS study, the Average CTDS Production Rates were compared with the mean observed Production Rate for the seven targeted Work Items. The one-sample t test was used for this comparison.

3.6.3 Driver Analysis

Procedures used for driver analysis are shown in Figure 3.4. Factors that are suspected to have significant effects on Production Rates and are known at the design stage were considered as Candidate Drivers. Once Candidate Drivers were identified, associated data were collected during regular job visits. Scatter plots were used to examine any relationships between observed Production Rates and each Candidate Driver. Drivers having no obvious relationship with observed Production Rates were excluded from further analysis. Based on the data attributes of the Candidate Drivers, two types of analysis approaches were used for further driver analysis. For those Candidate Drivers with continuous numerical data, regression analysis was conducted to identify drivers of Production Rates and to quantify their effects. For those Candidate Drivers with discrete numerical or categorical data, the ANOVA or t-test was used to test the difference in mean Production Rates for the subsets in each Candidate Driver.

According to the results from statistical analyses, the drivers were thus identified. The quantitative effects of drivers on Production Rates were also investigated. In addition, the correlations between identified drivers of each targeted item were computed to be used for reference on estimating effects of multiple drivers. If data were sufficient, multiple regression analysis was used to further investigate the interaction effects of multiple drivers.

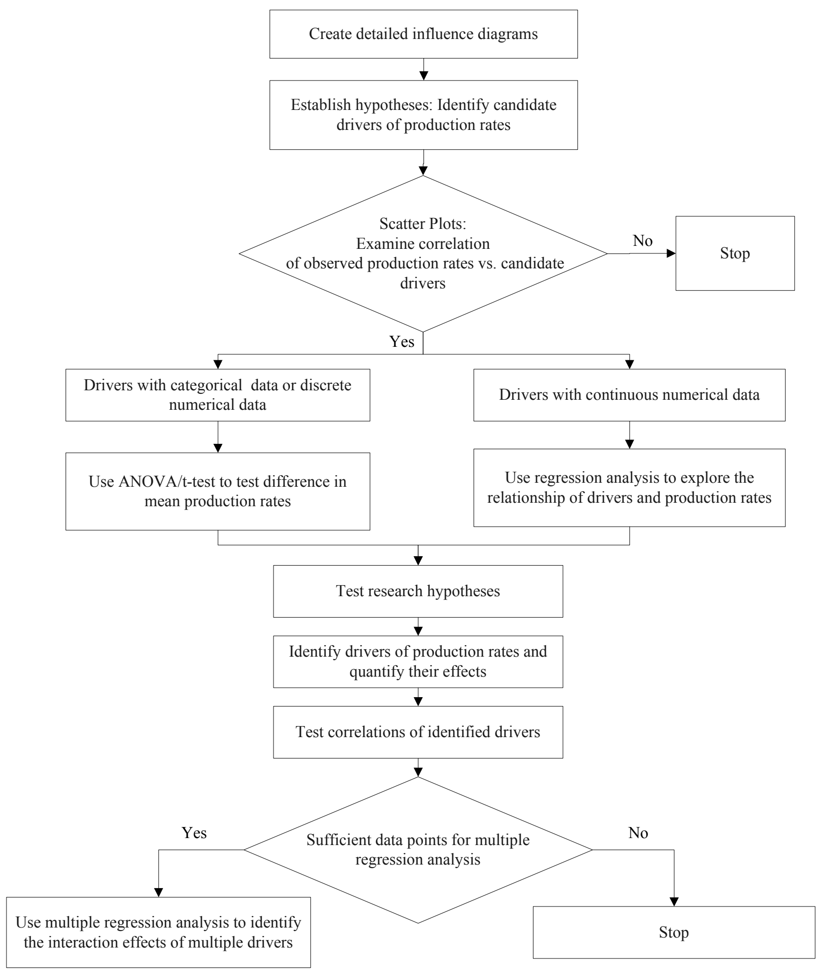


Figure 3.4 Flow Chart of Driver Analysis

3.6.3.1 Test of the Difference of Mean Observed Production Rates between Sub-groups of Candidate Drivers

The independent-samples t-test is one of the most popular methods of testing the differences between two population means. Three basic assumptions should be examined before applying the t-test. The three assumptions are as follows:

1. The two samples are independent
2. Populations are normally distributed
3. There are equal standard deviations between the two populations

If the two samples are not independent, the independent-sample t-test will not be efficient to test the differences in mean between the two groups and other test methods such as the paired-sample t-test may be used. The second assumption that the populations are normally distributed can be examined from Q-Q plots. If all data falls on a line with a 45 degree of slope on the Q-Q plot, a typical normal distribution can be identified. If this assumption is violated, the results of the t-test can only be used when the size of samples is reasonably large. The last assumption is that the standard deviations of two tested populations should be equal. This assumption can be examined from the results of Levene's test in the SPSS® version 11.0 for Windows. The result of the t-test may be incorrect if this assumption is violated, but the t-test can have an accurate result if the sample sizes are equal under this circumstance. These methods were applied in this study to verify some research hypotheses and to identify some Production Rate drivers.

3.6.3.2 Regression Analysis

Once a linear or non-linear relationship between two variables is observed from the scatter plot, a linear or non-linear regression analysis should be performed to verify if a relationship exists statistically. The form of estimating a regression model is $Y_i = b_0 + b_1 * X_{1i} + b2 * X_{2i}$. Y_i is the dependent variable that a study is trying to predict. X_{1i} and X_{2i} are the independent variables. In advance of conducting a regression analysis, the sample size should be checked if data are sufficient to perform it.

According to a study conducted by Green (1991), the required sample size for a regression analysis can be determined by four values which are α (the probability of making a type I error), 1-β (one minus the probability of making a type II error), R^2, and number of predictors. Table 3.4 displays the required sample sizes to test the hypothesis that the population multiple correlation equals zero with a power (1-β) of 0.8 and α of 0.05 based on power analysis (Green 1991). A regression model needs 24 data points for one predictor and 30 data points for two predictors when the α, 1-β, and R^2 values used to determine the statistical significance of a regression model are 0.05, 0.8 and 0.26, respectively. If the required R^2 used to determine the significance of a regression model increases, the number of data points can be reduced. In this study, the required R^2

is set as 0.34. Therefore, for this study a total of 20 data points are required to perform a simple regression analysis, and 26 data points are needed to perform a multiple regression analysis with two predictors. However, less than 20 data points may be also employed for a regression analysis if a higher R square is achieved.

Table 3.4 Sample Sizes Required to Test the Hypothesis that the Population Multiple Correlation Equals Zero with a Power of 0.80 and α of 0.05 (adopted from Green 1991)

Number of Predictors	Sample Sizes based on Power Analysis		
	R^2=0.02	R^2=0.13	R^2=0.26
1	390	53	24
2	481	66	30
3	547	76	35
4	599	84	39
5	645	91	42
6	686	97	46
7	726	102	48
8	757	108	51
9	788	113	54
10	844	117	56
15	952	138	67
20	1066	156	77
30	1247	187	94
40	1407	213	110

In addition, the logarithmic model (Equation 3.1) and the power model (Equation 3.2) were employed to identify non-linear relationships between selected cases with two variables. SPSS® version 11.0 for Windows was used to perform the linear and non-linear regression analyses.

$$\mathbf{Y_i = b_0 + b_1 * Log \quad X_i} \qquad \text{(Equation 3.1)}$$

$$\mathbf{Log \quad Y_i = Log \quad b_0 + b_1 * Log \quad X_i} \qquad \text{(Equation 3.2)}$$

Six steps are usually taken to perform a regression analysis. First, the dependent and independent variables should be checked to see if they are approximately normally distributed. The normal distributions of independent variables and dependent variable are basic assumptions of a regression analysis. Violation of this assumption would lead to a biased estimation due to lack of information. Secondly, a scatter plot is developed to check for a plausible linear model and a box plot is used to detect outliers. Outliers should be removed before performing a regression analysis because they impact the trend of the regression model. The third step is to fit the linear regression model and produce results of the regression analysis. In this step, the R^2, the adjusted R^2, and the P-values are computed. The next step is to inspect the R^2 of the fitted model.

The coefficient of determination, or R^2, is also called the measurement of the goodness of fit of the regression line. The value of R^2 is always between 0 and 1, and indicates the proportion of variation of dependent variables that can be explained by the prediction model. The formula (Albright et al. 1999, p583) for calculating R^2 in a simple linear model is shown in Equation 3.3.

$$\mathbf{R^2 = 1 - \frac{\sum e_i^{\ 2}}{\sum (Y_i - \overline{Y})^2}} \qquad \text{(Equation 3.3)}$$

$$\text{Where,}\ e_i = Y_i - \hat{Y}_i \ \text{ and } \ \hat{\mathrm{Y}}_\mathrm{i} = \mathrm{b}_0 + \mathrm{b}_1\mathrm{X}_\mathrm{i}$$

$$Y_i : \text{Observed Value;}\ \ \hat{Y}_i : \text{Fitted value of } \ Y_i$$

The fifth step is to inspect the results of testing coefficients for the fitted model. The t-test is applied to test coefficients. The P-values of the t-tests should be used to check if the coefficients of the fitted model are statistically different from 0. A P-value, less than α, indicates that the null hypothesis of a coefficient being equivalent to zero can be rejected at the (1- α) confidence interval. In contrast, a P-value, not less than α, represents that the tested coefficient is not statistically different from zero and thus, there is no relationship between the dependent variable and the independent variable. In this study, 0.05 and 0.1 were used as the value of α. The difference between applying 0.05 and 0.1 to hypothesis test is the level of confidence to conclude if the tested coefficient is significantly different from zero. The last step is to check for violation of model assumptions. Other than the approximate normal distribution of dependent and independent variable, three assumptions: (1) constant variance of errors; (2) normal distribution of errors; and (3) no high correlations between explanatory variables; should be checked.

The constant variance of errors can be examined by plotting the scatter plot of the predicted value of the fitted model versus the residuals. Non-constant variance of errors found in the regression model usually indicates the need for transformation of variables or adding another important variable. The normal distributions of variables and errors can be inspected by observing their Q-Q plots. If the data are perfectly normally distributed, the points in the Q-Q plot will "cluster around the 45° line. Any large deviations from a 45° line signal some type of non-normality" (Albright et al. 1999, p486).

3.6.3.3 Correlations Analysis

The Pearson product-moment correlation tests were used to check the correlations between the explanatory variables. The Pearson product-moment correlation, or γ, is a value between -1 and 1. A correlation equal to or near zero indicates no linear relationship existed between the two variables. On the other hand, a correlation with a magnitude close to 1 indicates a strong linear relationship.

CHAPTER IV: DATA COLLECTION PLAN AND EXECUTION

Reliable Production Rates estimation should include consideration of the impacts of drivers on Production Rates to reflect reality. Production Rates for Earthwork and Pavement Work Items and related factors were collected from thirty-five TxDOT on-going highway construction projects and analyzed statistically to investigate both the Production Rates and the drivers that have significant impacts on Production Rates. Such effects were quantified whenever possible.

4.1 RESEARCH HYPOTHESES

Several PMC members believed that the Production Rates in the CTDS for most Work Items in Earthwork and Pavement are too optimistic when compared to realistic rates. Pertaining to this issue, the first hypothesis was established as the following.

Hypothesis 1: The Production Rates of the CTDS are not realistic.

Production Rates for Earthwork and Pavement vary significantly due to the effects of productivity factors. Some productivity factors may have great influence on Production Rates. The second hypothesis was established based on this assumption and was specified as follows.

Hypothesis 2: The Production Rates of targeted Work Items are driven by some productivity factors that are known at the design stage.

4.2 CANDIDATE DRIVERS OF TARGETED WORK ITEMS

The purpose of this study was to investigate the Production Rates and identify the drivers that significantly influence Production Rates for Excavation, Embankment, Lime-treated sub-grade, Aggregate base course, Hot mix asphalt pavement, Slip-form concrete pavement and Conventional form concrete pavement. Influence diagrams were utilized to probe the possible drivers of Production Rates for each targeted Work Item. Factors directly or indirectly influencing Production Rates were listed in the influence diagrams. The results are intended to be used for Contract Time estimation at the design stage. Therefore, the factors identified in the influence diagram should be limited to those known at the design stage.

4.2.1 Candidate Drivers for Excavation

The influence diagram of the Production Rate (CY/Crew Day) for Excavation is shown in Figure 4.1. In the influence diagram, the factors were divided into three categories: project-level, work-zone level and work-item level. Only those factors that are known at the design stage appear in bolded circles in the influence diagram. These factors which were considered as the Candidate Drivers of the Production Rates of Excavation are listed as follows.

Project-Level:

1. Project Type: The type of project may influence the Production Rates of Excavation Operations due to different site layout, size of work, and strategies of traffic control.
2. Project Location: Project location may influence the Production Rates of Excavation Operations because of the availability of resources, site condition and traffic condition.
3. Traffic Flow: Traffic congestion may decreases Production Rates of haul trucks and therefore may reduce Production Rates of Excavation Operations.
4. Project Complexity: Projects with higher technical complexity may result in more interactions between different crews and, thus, may have more limitations on work space and accessibility and may affect Production Rates of Excavation Operations.
5. Accelerated Construction Provision: As a result of accelerated construction provision, contractors may contribute more resources and efforts to work on Excavation Operations. Therefore, projects with accelerated construction provision may have a higher average Production Rate.
6. Contractor Management Skill: Contractors with better management skill may have higher Production Rates of

Excavation due to appropriate supervising and resource allocation.

Work Zone-Level:

1. Work Zone Accessibility: Short distance and good haul road conditions result in more efficient transporting of excavated materials and, thus, may have higher Production Rates.
2. Work Zone Congestion: More space in a Work Zone to locate excavators, loaders and loading trucks, and for the waiting truck queue may increase the efficiency of loaders and, thus, may have higher Production Rates of Excavation.
3. Work Zone Drainage Effectiveness: The Production Rates of Excavation in Work Zones with less efficient drainage may be adversely affected as rain may worsen the condition of haul road.

Work Item-Level:

1. Work Area Quantity: Based on the fact that the greater the amount of repetitive work in a Work Area leads to more efficiency of work Operations and resource allocation. This may be true for Excavation because Excavation Operations are highly repetitive. In addition, productive hours in a working day may be higher for the Work Area with greater quantity.

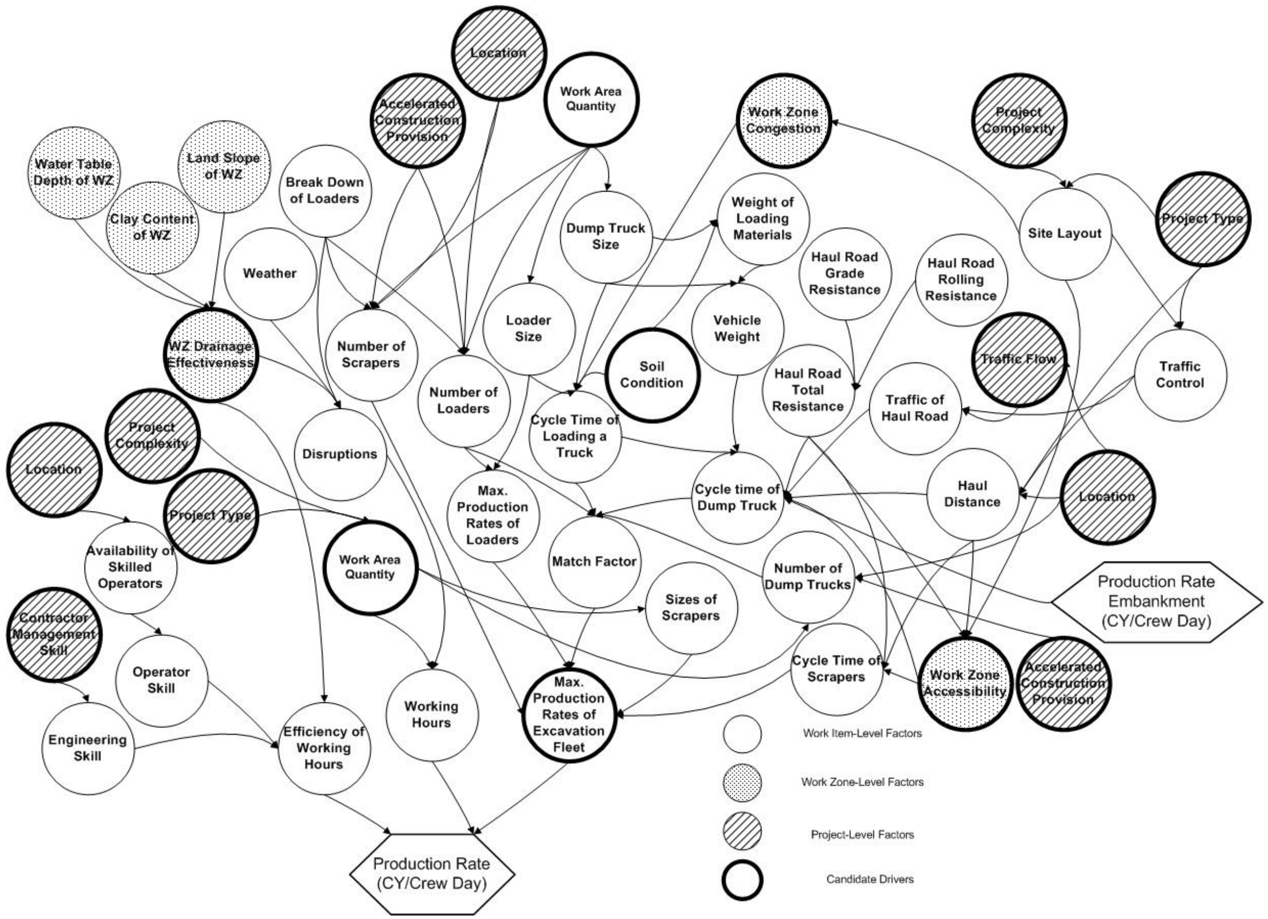


Figure 4.1 Influence Diagram of the Production Rate (CY/Crew Day) for Excavation

2. Soil Condition: Loose materials may be more easily excavated and therefore may have a better average Production Rate.

4.2.2 Candidate Drivers for Embankment

The influence diagram of the Production Rate (CY/Crew Day) for Embankment is shown in Figure 4.2. The Candidate Drivers are listed as follows:

Project-Level:

1. Project Type: The type of project may influence the Production Rates of Embankment Operations due to size of work, working sequence, and strategies of traffic control.
2. Project Location: Project location may influence the Production Rates of Embankment Operations due to traffic conditions.
3. Traffic Flow: Traffic congestion usually decreases the Production Rates of haul trucks and therefore may reduce the Production Rates of Embankment Operations.
4. Project Complexity: Projects with higher technical complexity may result in more interactions between different crews and, thus, may have more limitations on work space and accessibility. This too, may affect Production Rates of Embankment Operations.

5. Accelerated Construction Provision: As a result of accelerated construction provision, contractors may contribute more resources and efforts to work on Embankment Operations. Therefore, projects with accelerated construction provision may have a higher average Production Rate.

6. Contractor Management Skill: Contractors with better management skills may have higher production due to appropriate supervision and resource allocation.

Work Zone-Level:

1. Work Zone Accessibility: Short distance and good haul road condition are more efficient for transporting excavated materials and so may have a better average Production Rate.

2. Work Zone Congestion: Large free space in the Work Zone allows for unloading, furthermore spreading and compacting can be operated simultaneously. This may increase the Production Rates of Embankment Operations.

3. Work Zone Drainage Effectiveness: Work Zones with less efficient drainage may have interruptions on transporting of materials after rain due to the wet condition of haul road. It may also influence the efficiency of compaction because of excessive water content. Work Zone drainage effectiveness

may be a driver of the Production Rates on Embankment Operations.

Work Item-Level:

1. Work Area Quantity: Repetition leads to more efficient work Operations and resource allocation. This may be applicable for Embankment because these Operations are high repetitive. In addition, productive hours in a working day may be higher for the Work Area with greater quantity.
2. Soil Conditions: Soil conditions will influence the required number of compaction passes to achieve the designed density, therefore affecting Production Rate.

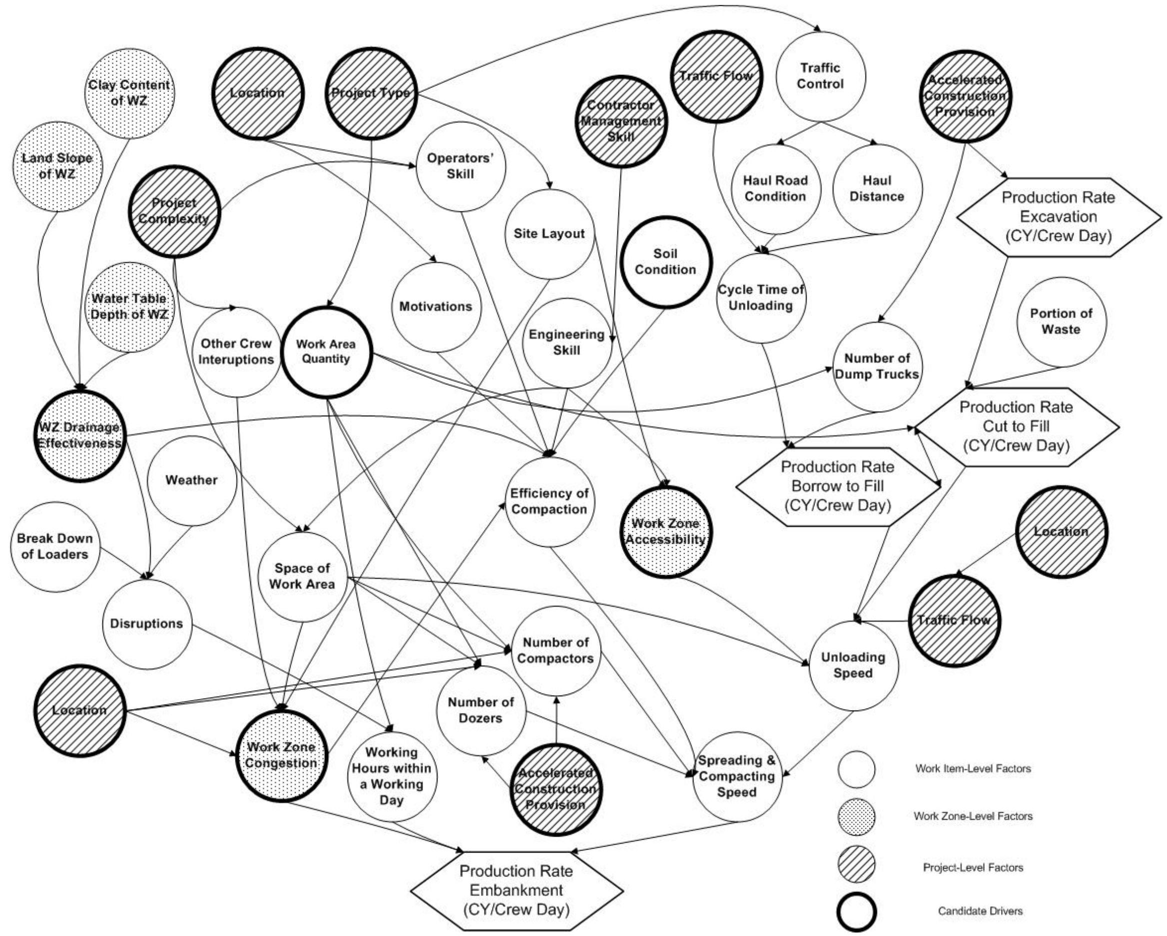


Figure 4.2 Influence Diagram of the Production Rate (CY/Crew Day) for Embankment

4.2.3 Candidate Drivers for Lime-Treated Sub-grade

The influence diagram of the Production Rate (SY/Crew Day) for Lime-treated sub-grade is shown in Figure 4.3. The Candidate Drivers are listed as follows:

Project-Level:

1. Project Type: The type of Project may influence the Production Rates of Lime-treated sub-grade Operations due to different site layout, size of work, and dispersion of work.
2. Project location: The layout of drive ways and intersections in rural, urban and metro areas are very different. This may have different impacts on dispersion of work and thus, may influence the Production Rates of Lime-treated sub-grade Operations.
3. Project Complexity: Projects with higher technical complexity may lower the average Production Rate of Lime-treated sub-grade for various reasons, for example higher interactions between different crews and highly dispersed works.
4. Accelerated Construction Provision: As a result of accelerated construction provision, contractors may put more resources and effort to work on Lime-treated sub-grade Operations. Therefore, projects with accelerated construction provision may have a higher average Production Rate.

5. Contractor Management Skill: Contractors with better management skill may have higher Production Rates due to better supervision and resource allocation.

Work Zone-Level:

1. Work Zone Congestion: A large Work Zone may allow mixing, compacting and finishing simultaneously and may have higher Production Rates of Lime-treated sub-grade Operations.
2. Work Zone Clay Content: The Work Zone with higher clay content needs more lime for the treatment of the soil. Therefore, the mixing speed may be slower so the Production Rates of Lime-treated sub-grade may be lower.
3. Work Zone Land Slope: The slope of a Work Zone will affect the speed of operating equipment and influence the efficiency of elevation and grade control.

Work Item-Level:

1. Work Area Quantity: Lime-treated sub-grade Operations may experience increasing productivity as it is highly repetitive. In addition, productive hours in a working day may be higher for the Work Area with greater quantity.
2. Length of Work Area: When the number of repetitions increases, Production Rates will be higher due to learning

effects. A longer Work Area means this work function can expect increasing productivity.

3. Type of Lime Used: The required duration of curing may vary according to types of lime used, therefore it may influence the average Production Rate of Lime-treated sub-grade.

4. Lift-Thickness: The construction time of mixing and compacting may be longer in a thicker lift and thus, the Production Rates in a thicker lift may be lower.

5. Soil Condition: The condition of soil may influence the speed of mixing and compacting.

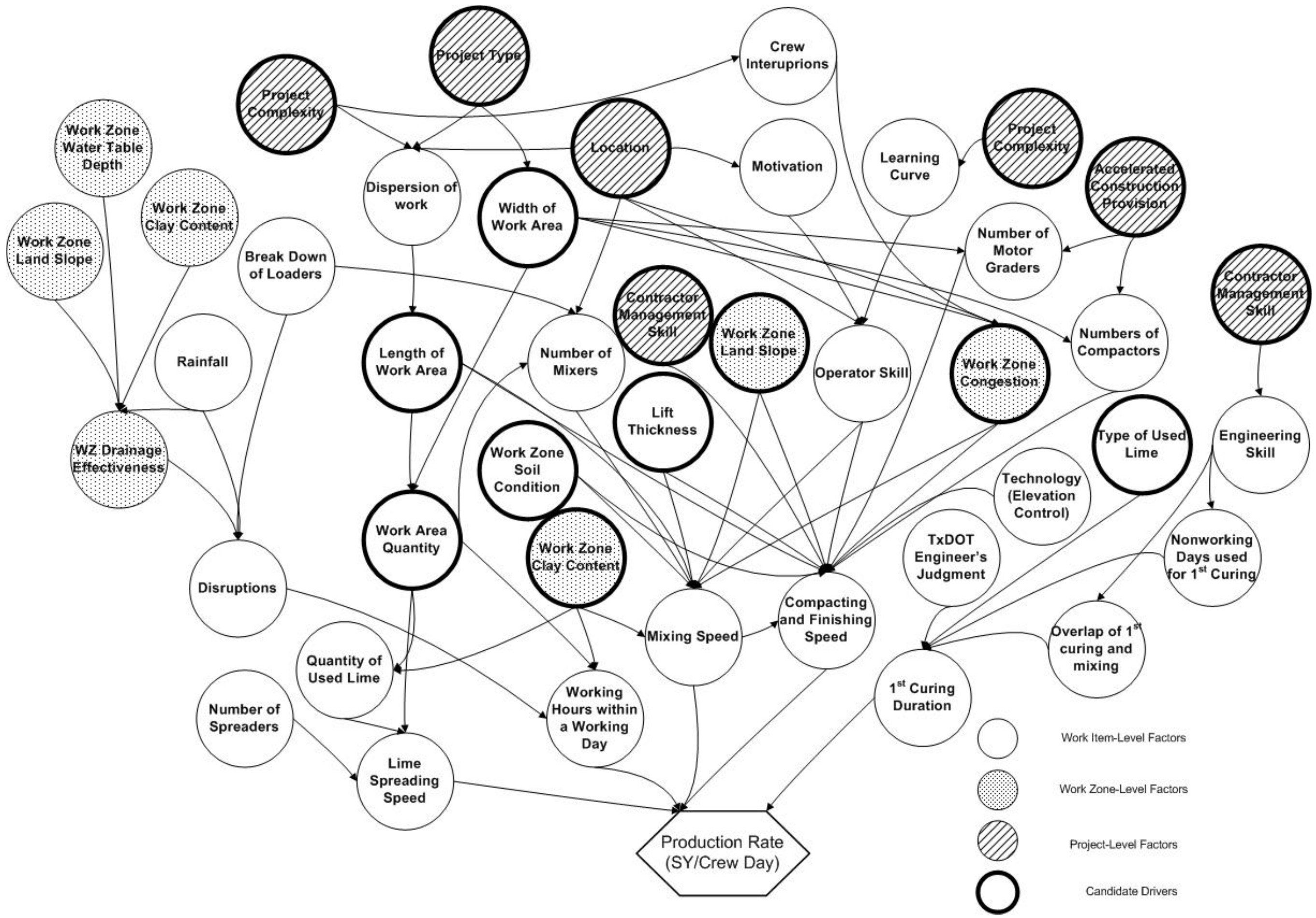


Figure 4.3 Influence Diagram of the Production Rate (SY/Crew Day) for Lime-Treated Sub-grade

4.2.4 Candidate Drivers for Aggregate Base Course

The influence diagram of the Production Rate (Lift-SY/Crew Day) for Aggregate base course is shown as Figure 4.4. The Candidate Drivers are listed as follows:

Project-Level:

1. Project Type: The type of project may influence the Production Rates of Aggregate base Operations due to different site layout size of work and dispersion of work.
2. Project Location: The layout of drive ways and intersections in rural, urban and metro areas are very different. This may influence the Production Rates of Aggregate base construction.
3. Project Complexity: Projects with higher technical complexity may have lower Production Rates of Aggregate base Operations.
4. Accelerated Construction Provision: Projects with accelerated construction provision may have higher Production Rates.
5. Contractor Management Skill: Contractors with better management skill may have higher Production Rates.

Work Zone-Level:

1. Work Zone Congestion: Large Work Zones may allow spreading, compacting, and finishing simultaneously and thus, may have better average Production Rates.
2. Work Zone Land Slope: The slope of a Work Zone will affect the speed of operating equipment and the efficiency of elevation and grade control.

Work Item-Level:

1. Work Area Quantity: Aggregate base may over time experience increasing productivity because its Operations are highly repetitive. In addition, productive hours in a working day may be higher for the Work Area with greater quantity.
2. Lift-Length of Work Area: The longer the Lift-length of a Work Area for Aggregate base the more the number of repetitions there will be. When the number of repetitions increases, Production Rates will be higher due to learning effects.
3. Width of Work Area: A wider Work Area may allow more equipment to work at the same time and thus may have higher average Production Rates.
4. Lift-Thickness: The construction time of compacting may be longer in a thicker lift. Therefore, the Production Rates of Aggregate base in a thicker lift may be lower.

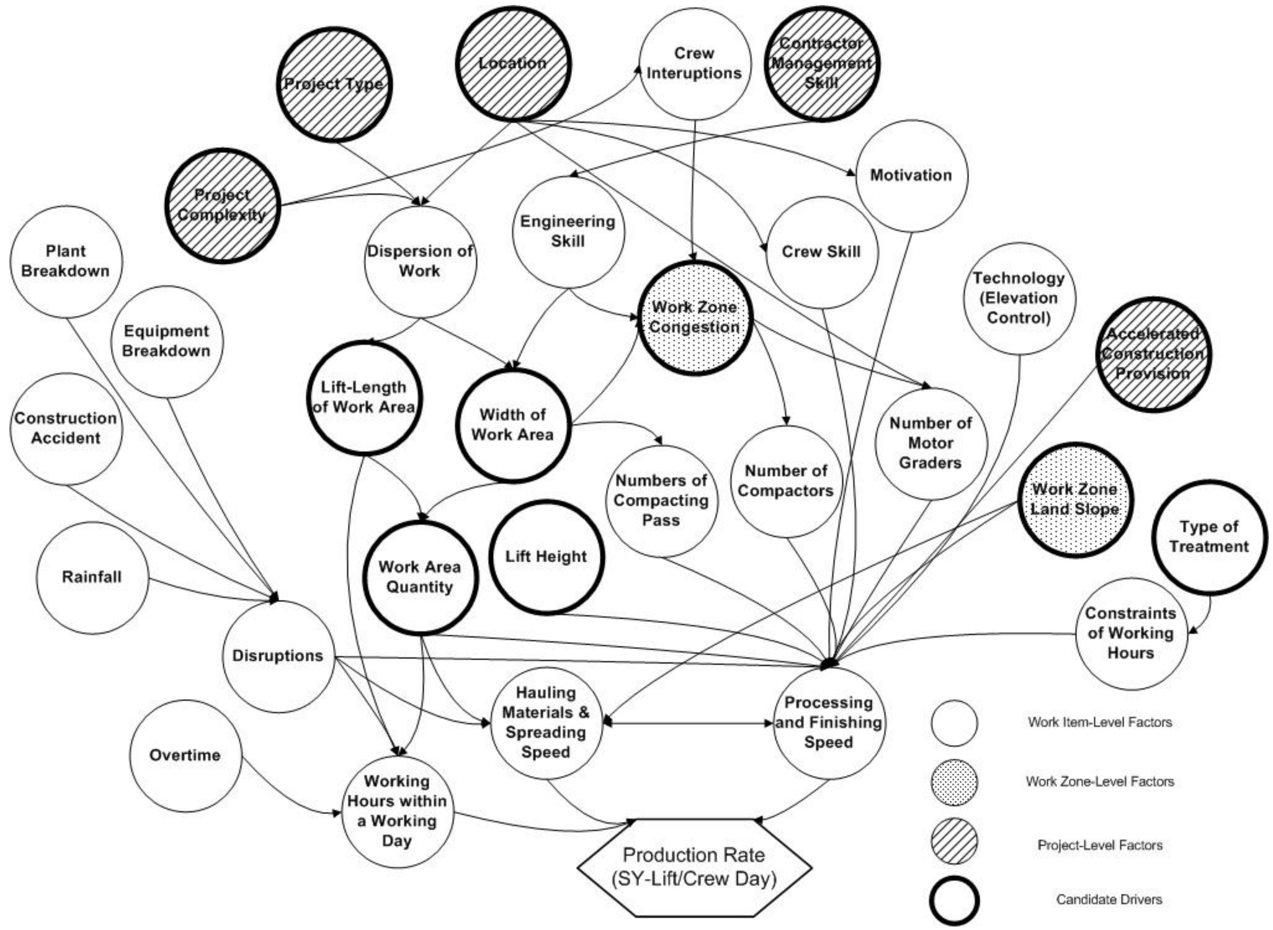


Figure 4.4 Influence Diagram of the Production Rate (Lift-SY/Crew Day) for Aggregate Base Course

4.2.5 Candidate Drivers for Hot Mix Asphalt Pavement

The influence diagram for the Production Rate (Ton/Crew Day) of Hot mix asphalt pavement is shown in Figure 4.5. The Candidate Drivers are listed as follows:

Project-Level:

1. Project Type: The type of project may influence the Production Rates of Hot mix asphalt pavement Operations due to different site layout, size of Hot mix asphalt, strategies of traffic control and dispersion of work.
2. Project Location: The frequency of drive ways and intersections in rural, urban and metro area are very different. This may have different impacts on dispersion of work and, thus, may influence the Production Rates of Hot mix asphalt pavement. In addition, the traffic condition in different type of location may have an impact on the Production Rates.
3. Traffic Flow: Traffic flow may influence the Production Rates of Hot mix asphalt pavement Operations because it influences the efficiency of logistics.
4. Project Complexity: Projects with higher technical complexity may result in more interactions between work and traffic. This

may lead to high dispersion of work and thus, may lead to lower productivity.

5. Accelerated Construction Provision: As a result of accelerated construction provision, contractors may put more resources and effort into work on Hot mix asphalt pavement Operations, leading to a higher average Production Rate.

6. Contractor Management Skill: Contractors with better management skills may have higher Production Rates of Hot mix asphalt pavement due to better supervision, engineering and resource allocation.

Work Zone-Level:

1. Work Zone Accessibility: Working in easily accessible Work Zones, contractors can better manage the transportation of Hot mix asphalt and may reduce the frequency of interruptions due to material shortage. Therefore, a better average Production Rate may be expected when working in easily accessible Work Zones.

2. Work Zone Congestion: Working in congested Work Zones, contractors may need more time to unload Hot mix asphalt and thus, increase the waiting time of the lay-down machine. They may have lower Production Rates.

3. Work Zone Land Slope: The slope of a Work Zone may influence the speed of operating equipments and affect the efficiency of elevation and grade control. Therefore, slope may influence the Production Rate of Hot mix asphalt Operations.

Work Item-Level:

1. Work Area Quantity: Increased repetition in a Work Area leads to more efficiency. This may be true for Hot mix asphalt pavement because its Operations are highly repetitive. In addition, productive hours in a working day may be higher for the Work Area with greater quantity.
2. Course Type: The Surface course is usually built with a higher standard of quality as compared to the Base course. Therefore, a lower average Production Rate of the Surface course may be expected.
3. Main Lane vs. Non-main Lane Application: The location of work such as on the main lane, the frontage road, or on a ramp may influence the Production Rates of Hot mix asphalt Operations due to dispersion of work. The main lane usually has lesser dispersion of Hot mix asphalt work than the frontage

road or on a ramp. The Production Rates of Hot mix asphalt in the main lane may be higher than other areas.

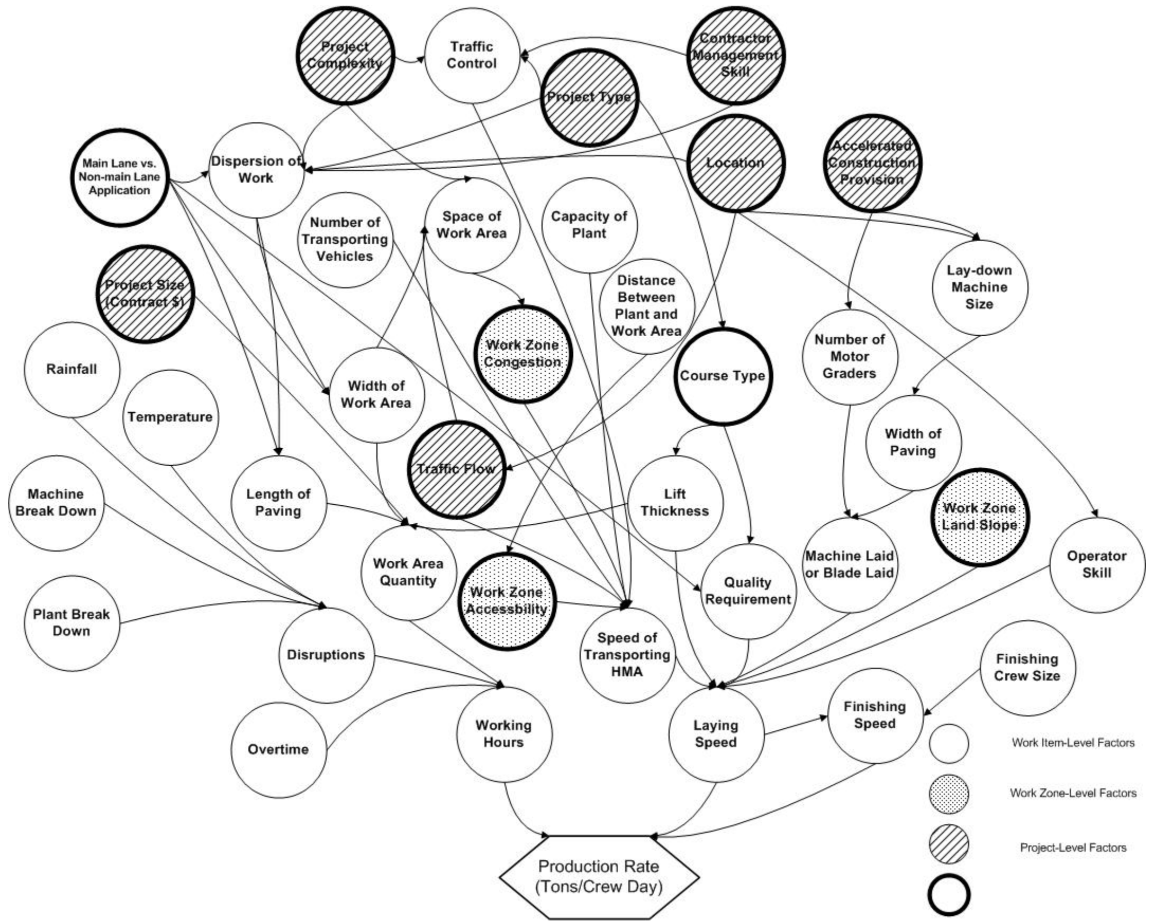


Figure 4.5 Influence Diagram of the Production Rate (Ton/Crew Day) for Hot Mix Asphalt Pavement

4.2.6 Candidate Drivers for Slip-form Concrete Pavement

The influence diagram of the Production Rate (SY/Crew Day) for Slip-form concrete pavement is shown as Figure 4.6. The Candidate Drivers are listed as follows:

Project-Level:

1. Project Type: The type of project may influence the Production Rates of Slip-form concrete pavement Operations due to different site layout, size of work and dispersion of work.
2. Project Location: Rural, urban and metro area may have very different impacts on dispersion of work and thus, may influence the Production Rates of Slip-form concrete pavement.
3. Project Complexity: Projects with higher technical complexity will result in more interactions between different crews and may lead to lower average Production Rates of Slip-form concrete pavement.
4. Traffic Flow: Traffic flow can affect the efficiency of logistics which may influence the Production Rates of Slip-form concrete pavement.
5. Accelerated Construction Provision: As a result of accelerated construction provision, contractors may put more resources and effort into work on Slip-form concrete pavement Operations.

Projects with accelerated construction provision, thus they may have a higher average Production Rate.

6. Contractor Management Skill: Contractors with good management may have higher Production Rates of Slip-form concrete pavement due to better supervision, engineering and resource allocation.

Work Zone-Level:

1. Work Zone Accessibility: Working in easily accessible Work Zones, contractors can better manage the transportation of concrete so that the frequency of interruptions due to materials shortage may be reduced. Therefore, a higher average Production Rate may be expected in easily accessible Work Zones
2. Work Zone Congestion: Large Work Zones will allow transit-mix trucks to wait in the Work Zone, which may reduce the waiting time due to materials shortage. Therefore, Work Zones with less congestion may have higher Production Rates.
3. Work Zone Land Slope: The slope of a Work Zone may influence the speed of a paver, the transition time of locating transit-mix trucks, and the duration of grading. Therefore, the

land slope of a Work Zone may be a driver of the Production Rate of Slip-form concrete pavement Operations.

Work Item-Level:

1. Type of Concrete Pavement: Three types of Slip-form concrete pavement are used in Texas. Each has a different scope of work, for example, reinforced concrete pavement may require more working days on rebar installation than the other two types. Therefore, the reinforced concrete pavement may have a lower average Production Rate than other two types. In addition, productive hours in a working day may be higher for the Work Area with greater quantity.
2. Work Area Quantity: Based on the fact that the greater the amount of repetitive work in a Work Area the more efficient the work Operations and resource allocation will be, Slip-form concrete pavement may experience better Production Rate because its Operations are highly repetitive.
3. Length of Work Area: The longer the length of a Work Area for Slip-form concrete pavement the more the number of repetitions there will be. When the number of repetitions increases, Production Rates will be higher due to learning effects.

4. Width of Work Area: A wider Work Area usually has minor problems of congestion and it is convenient for transit-mix trucks to wait and unload concrete. Therefore, a wider Work Area may have a better Production Rate.

5. Thickness of Concrete Pavement: Thicker concrete pavement needs more concrete for a certain area. Therefore, it requires more time for unloading and consolidating of poured concrete and thus, may have lower Production Rates.

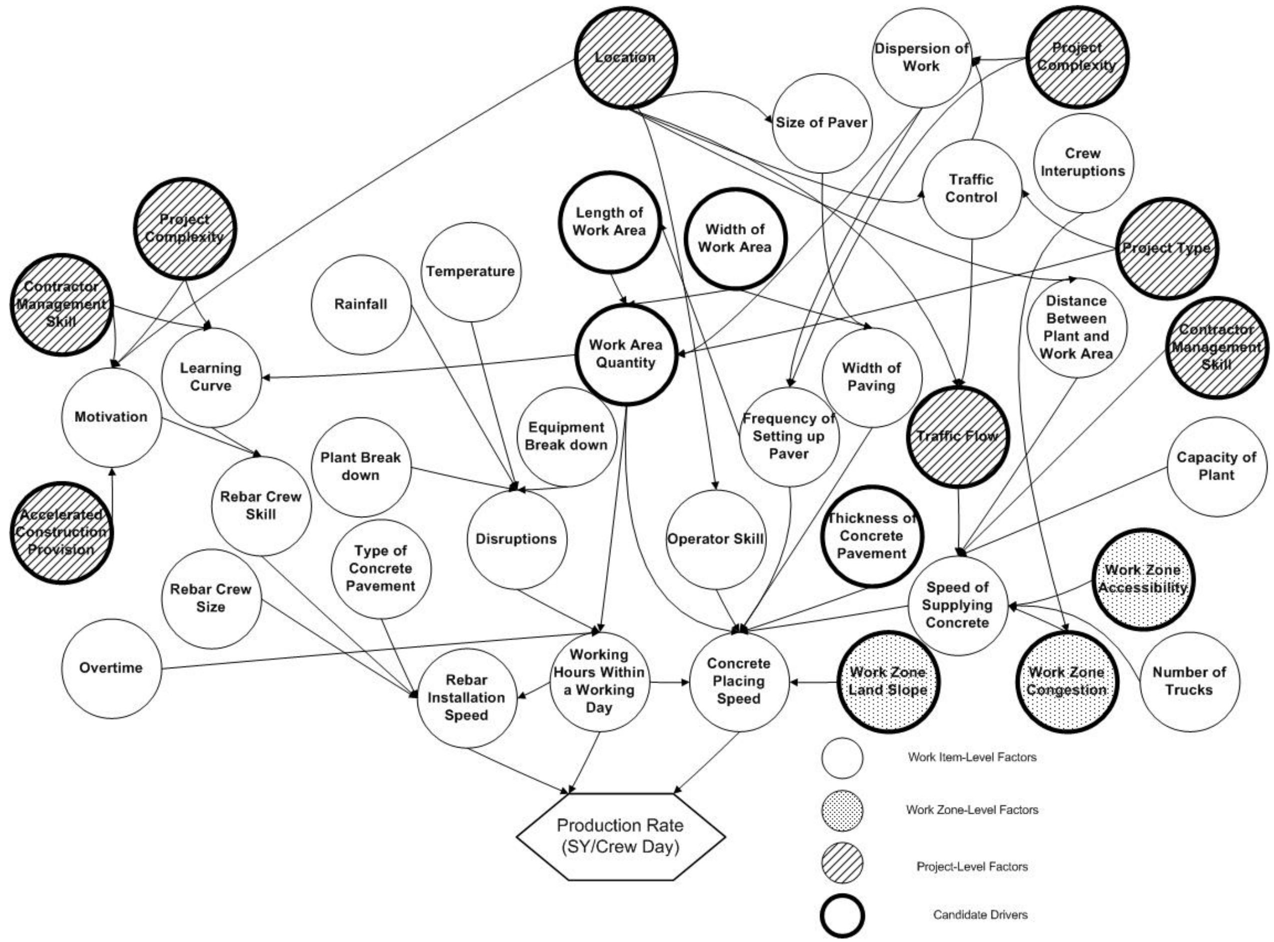


Figure 4.6 Influence Diagram of the Production Rate (SY/Crew Day) for Slip-form Concrete Pavement

4.2.7 Candidate Drivers for Conventional Form Concrete Pavement

The influence diagram of the Production Rate (SY/Crew Day) for Conventional form concrete pavement is shown as Figure 4.7. The Candidate Drivers were listed as follows.

Project-Level:

1. Project Type: The type of project may influence the Production Rates of Conventional form concrete pavement Operations.
2. Project Location: Project location may influence the Production Rates of Conventional form concrete pavement Operations due to its impact on traffic conditions.
3. Project Complexity: Projects with higher technical complexity may have lower Production Rates.
4. Traffic Flow: Traffic flow affects the efficiency of logistics and thus, may influence the Production Rates of Conventional form concrete pavement.
5. Accelerated Construction Provision: Projects with accelerated construction provision may have a higher average Production Rate.
6. Contractor Management Skill: Contractors with better management skills may have higher Production Rates.

Work Zone-Level:

1. Work Zone Accessibility: Working in easily accessible Work Zones may lead to higher Production Rates.
2. Work Zone Congestion: Work Zone with large space may allow transit-mix truck to wait in the Work Zone and thus, reduce the waiting time due to material shortage and the transition duration of unloading concrete. Therefore, Work Zones with less congestion may have better Production Rates.
3. Work Zone Land Slope: The slope of a Work Zone may influence the transition duration of unloading of transit-mix trucks, and have an impact on the duration of grading and finishing. Therefore, Work Zone land slope may influence the Production Rates.

Work Item-Level:

1. Work Area Quantity: The repetitive nature of conventional from concrete pavement may allow for increasing productivity. In addition, productive hours in a working day may be higher for the Work Area with greater quantity.
2. Configuration of Concrete Pavement: When the Configuration of Concrete Pavement has any curve or sharp angle, the duration of performing the formwork and rebar installation for this

Concrete Pavement may be longer than the Concrete pavement that has a Configuration without any curve or sharp angle. Therefore, a lower average Production Rate may be expected for the Concrete pavement for the former Configuration.

3. Thickness of Concrete Pavement: A thicker depth concrete pavement usually needs more concrete to complete a fixed area. It may also require more time for unloading and consolidating of poured concrete. Therefore, a lower average Production Rate may be expected.

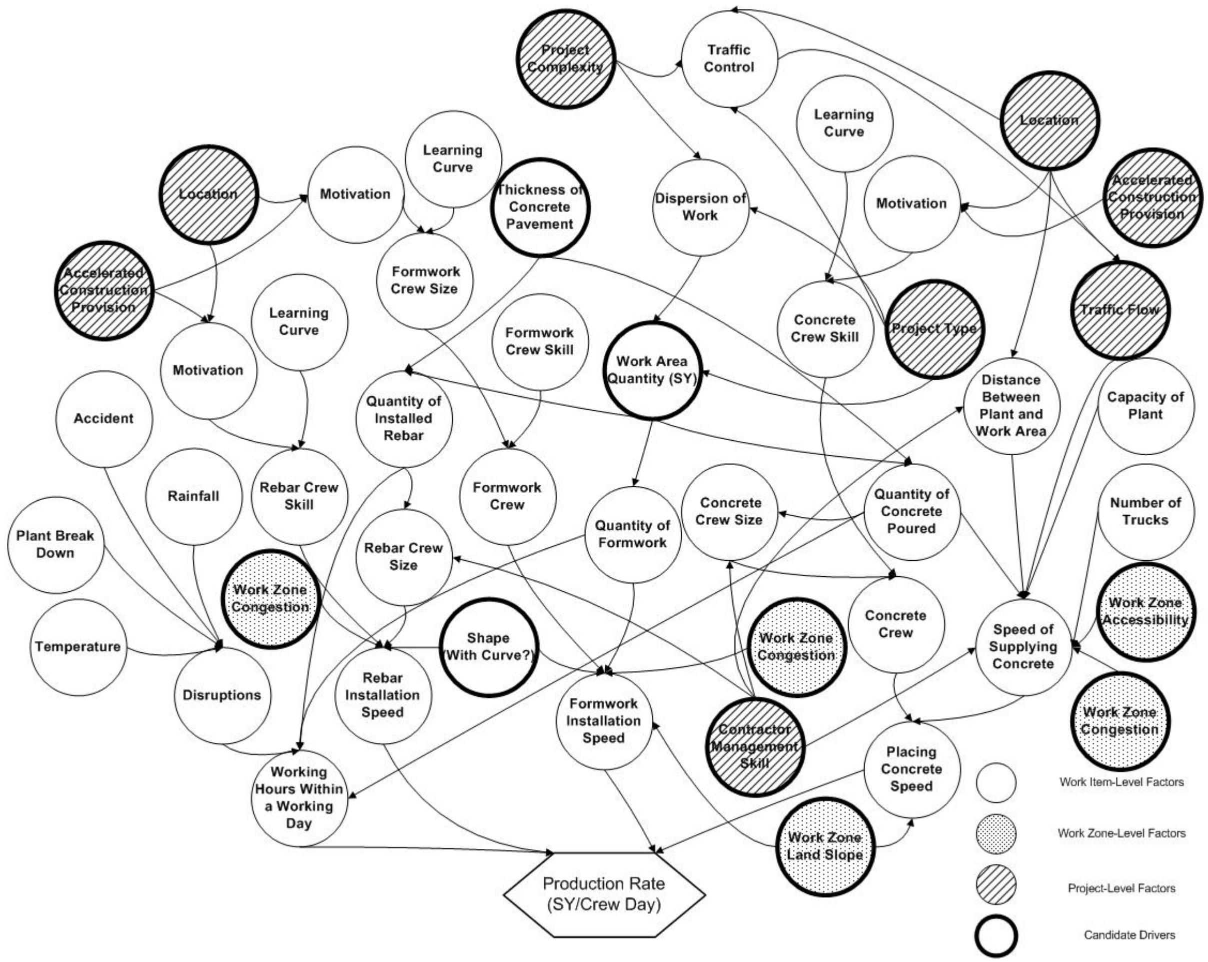


Figure 4.7 Influence Diagram of the Production Rate (SY/Crew Day) for Conventional form Concrete Pavement

Table 4.1 summarizes the selected Candidate Drivers for the seven targeted Work Items. Data attributes of the Candidate Drivers at the project-level are displayed in the project-level data collection tool. Candidate Drivers at the Work Zone-level were discussed in detail in Section 4.4.2. Table 4.2 displays data attributes of Candidate Drivers at the Work Item-level. These Candidate Drivers were further investigated in the driver analysis of Chapter 6 and 7.

Table 4.1 Candidate Drivers vs. Seven Targeted Work Items

	Candidate Drivers	Excavation	Embankmant	Lime-Treatment Sub-grade	Aggregate Base (Flexible Base and CTB)	Hot Mix Asphalt Pavement	Slip-from Concrete Pavement	Conventional Form Concrete Pavement
Project Level	Project Type	X	X	X	X	X	X	X
	Project Location	X	X	X	X	X	X	X
	Traffic Flow	X	X			X	X	X
	Project Complexity	X	X	X	X	X	X	X
	Accelerated Construction Provision	X	X	X	X	X	X	X
	Contractor Management Skill	X	X	X	X	X	X	X
Work Zone Level	Work Zone Accessibility	X	X			X	X	X
	Work Zone Congestion	X	X	X	X	X	X	X
	Work Zone Drainage Effectiveness	X	X					
	Work Zone Clay Content			X				
	Work Zone Land Slope			X	X	X	X	X
Work Item Level	Work Area Quantity	X	X	X	X	X	X	X
	Soil Condition	X	X	X				
	Length of Work Area			X	X (Lift-Length)		X	
	Type of Lime Used			X				
	Thickness			X	X (Lift)		X	X
	Width of Work Area				X		X	
	Course Type					X		
	Main Lane vs. Non-main Lane					X		
	Type of Concrete Pavement						X	
	Configuration							X

Table 4.2 Work Item Level Candidate Drivers and Data Attributes

Excavation (Unit: CY/Crew Day)			
Work Area Quantity	(Numerical: CY)		
Soil Condition	Loose	Stiff	Rocky
Embankment (Unit: CY/Crew Day)			
Work Area Quantity	(Numerical: CY)		
Soil Condition	Loose	Stiff	Rocky
Lime-treated Sub-grade (Unit: SY/Crew Day)			
Work Area Quantity	(Numerical: SY)		
Length of Work Area	(Numerical: LF)		
Type of Lime Used	Type C Lime	Others	
Lift-Thickness	(Numerical: INCH)		
Soil Condition	Loose	Stiff	Rocky
Aggregate Base Course (Unit: Lift-SY/Crew Day)			
Work Area Quantity	(Numerical: Lift-SY)		
Lift-Length of Work Area	(Numerical: LF)		
Width of Work Area	(Numerical: LF)		
Lift-Thickness	(Numerical: INCH)		
Hot Mix Asphaltic Concrete Pavement (Unit: Ton/Crew Day)			
Work Area Quantity	(Numerical: TON)		
Course Type	Base	Surface	
Main Lane vs. Non-main Lane	Main Lane	Non-main Lane	
Slipform Concrete Pavement (Unit: SY/Crew Day)			
Type of Concrete Pavement	CRCP	JCP	NRCP
Work Area Quantity	(Numerical: SY)		
Length of Work Area	(Numerical: LF)		
Width of Work Area	(Numerical: LF)		
Thickness	(Numerical: INCH)		
Conventional Form Concrete Pavement (Unit: SY/Crew Day)			
Work Area Quantity	(Numerical: SY)		
Configuration (Curve or Sharp Angle)	None	Yes	
Thickness	(Numerical: INCH)		

4.3 Data Collection Tools

A package of data collection tools consisting of project-level data collection, Work Zone-level and Work Item-level data collection and Work Items sheets was developed.

4.3.1 Project-Level Data Collection Tool

The project-level data collection tool, shown in Appendix C, consists of three major parts. The first section documents general project information including the name of the road, station range, prime general contractor, project duration, percentage of completion, as well as city and county. The second section helps identify Work Items from the TxDOT site personnel according to their planned schedule. Such information in this section allows data collectors to pin-point their Work Items and to reflect on projects in which they would be interested. The last section was used by data collectors to evaluate the characteristics of the selected projects. The information collected for this section includes project type, location, traffic flow, traffic account, annual precipitation, winter season length, percentage of completion, contract amount, technical complexity, contract day, accelerated construction provision, liquidated damages, soil types, clay content, land slope, water table depth below grade, scheduling technique used, days per week, hours per day, contract administration system and contractor's management skill.

4.3.2 Work Zone-level and Work Item-level

The Work Zone- and Work Item-level data collection tool is shown in Appendix D.

4.3.2.1 Work Zone-Level

Six Work Zone (WZ)-level factors were identified as the possible factors influencing the Production Rates of highway construction: accessibility, congestion, drainage effectiveness, clay content, land slope and water table depth. The measurements of these six factors are discussed in the following sections.

Due to the complexity of construction task, the Work Zone defined for each type of construction tasks may vary in terms of its physical outline, and thus the six factors were measured in different ways.

4.3.2.1.1 WZ Accessibility

Work Zone accessibility in this study was characterized in one of three ways: difficult, moderate and easy. According to the Candidate Drivers selected in Section 4.1, Work Zone accessibility influences the Production Rates of Excavation, Embankment, Hot mix asphalt pavement, and Concrete pavement.

For Excavation and Embankment, rolling resistance, grade resistance, and haul road distance can influence the travel time of hauling materials (Simon 1999; Peurifoy et al. 2002) Therefore, the different levels of Work Zone accessibility are defined as follow:

Difficult
- Haul distance is greater than ten miles, *or*
- Haul distance is less than ten miles but greater than five miles and the access road has high total resistance

Moderate
- Haul distance is less than ten miles but greater than five miles and the access road has low total resistance, *or*
- Haul distance is less than five mile but greater than one mile, and the access road has high total resistance

Easy
- Haul distance is greater than one mile but less than five miles and the access road has low total resistance, *or*
- Haul distance is less than one mile

For Hot mix asphalt pavement and Concrete pavement, the Work Zone accessibility measurement was based on the distance between the Hot mix asphalt plant or concrete batch plant and the Work Area and the ease of accessing the Work Area by the transporting trucks.

Difficult
- Haul distance is greater than ten miles, *or*
- Access road is not well constructed

Moderate
- Haul distance is less than ten miles but greater than five miles, *or*
- Access road is not well maintained

Easy
- Haul distance is less than five miles, *and*
- Access road is well maintained

4.3.2.1.2 WZ Congestion

Ovararin and Popescu (2001) defined Work Zone congestion as the frequency of additional crews working in the same Work Area. In this study, working procedures are very different among the selected seven Work Items, so it was necessary to separate the definition of the Work Zone congestion for each Work Item. According to the Candidate Drivers selected in Section 4.1, Work Zone congestion influenced the Production Rates of all seven targeted Work Items.

For Excavation, Work Zone congestion refers to the space allowed for the truck queue when loading and the space allowed for the excavators to perform Excavation and loading.

Severe
- There is no other space in the Work Zone for the truck queue waiting to load, *and*
- There is limited space for loaders to load trucks

Moderate
- There is free space for loaders but there is limited space in the Work Zone for truck queue waiting for loading

Minor
- There is free space for loaders and truck queue

For Embankment, Work Zone congestion refers to the space allowed in the Work Zone for unloading, spreading, and compacting.

Severe
- Work Zone allows only one of tree different tasks (Dumping, Spreading, or Compacting) at a time

Moderate
- Work Zone area allows only two different tasks

simultaneously

Minor ● Work Zone allows three tasks simultaneously

For Lime-treated sub-grade, Work Zone congestion refers to the space allowed in the Work Zone for mixer, motor grader and compactor to work simultaneously.

Severe ● Only one piece of equipment can be operated each time

Moderate ● Two out of three pieces of equipment can be operated simultaneously

Minor ● Mixer, motor grader, and compactor can work simultaneously

For Aggregate base course, Work Zone congestion refers to the space allowed in the Work Zone for the motor grader and compactors to work simultaneously.

Severe ● Only one piece of equipment can be operated at a time

Moderate ● Two out of three pieces of equipment can be operated simultaneously

Minor ● More than three pieces of equipment can work simultaneously

For Hot mix asphalt (HMA) pavement, Work Zone congestion refers to the space allowed in the Work Zone for unloading the truck and the waiting truck queue.

Severe ● Work Zone area is adjacent to heavy traffic and has limited space for unloading Hot mix asphalt

Moderate ● Work Zone area is not adjacent to heavy traffic but has limited space for unloading Hot mix asphalt or waiting trucks

Minor ● Work Zone area has enough space for unloading HMA and truck queue

For Slip-form concrete pavement, Work Zone congestion refers to the space allowed in the Work Zone for installing rebar and unloading concrete.

Severe ● Work Zone area is adjacent to heavy traffic and has limited space for installing rebar and unloading concrete

Moderate ● Work Zone area is not adjacent to heavy traffic but has limited space for unloading concrete or for a truck queue

Minor ● Work Zone area has enough space for installing rebar, unloading concrete and for the truck queue

For Conventional form concrete pavement, Work Zone congestion refers to the space allowed in the Work Zone for installing rebar and unloading concrete.

Severe ● Work Zone area is adjacent to heavy traffic and has limited space for unloading concrete and eight rebar workers

Moderate ● Work Zone area is not adjacent to heavy traffic but has limited space for unloading concrete or eight rebar workers

Minor ● Work Zone area has enough space for unloading concrete and eight rebar workers

4.3.2.1.3 WZ Drainage Effectiveness

Work Zone drainage effectiveness is a measurement of the frequency of flooding after rain. According to the Candidate Drivers selected in Section 4.1, this Candidate Driver only influenced the Production Rates of Excavation and Embankment Operations. This Candidate Driver was based on TxDOT site personnel's judgment since they were in charge of assessing the site condition when it rained.

Easily Flooded	●	Frequently floods after rain
Moderate	●	Sometimes floods after a heavy rain
Quickly Drains	●	Rarely floods after rain

4.3.2.1.4 WZ Clay Content

According to the Candidate Drivers selected in Section 4.1, only the Production Rates of Excavation, Embankment and Lime-treated sub-grade were influenced by clay content. The clay content was evaluated based on the judgment of site personnel.

High	●	Soil becomes very sticky after rainfall
Moderate	●	Soil becomes somewhat sticky after rainfall
Low	●	Soil does not become sticky after rainfall

4.3.2.1.5 WZ Land Slope

Land slope affects the Production Rates of all seven targeted Work Items. The land slope of the Work Zone was determined during site visits.

Steep
- The slope of the Work Zone is greater than 15°

Moderate
- The slope of the Work Zone is greater than 5° but less than 15°

Flat
- The slope of Work Zone is less than 5°

4.3.2.1.6 WZ Water Table Depth

Excavation and Embankment Operations are affected by the Water table depth. The Water table depth was measured by TxDOT site personnel.

>10'
- The typical water table is more than 10' below the original ground level

4'~10'
- The typical water table is between 4' and 10' below the original ground level

<4'
- The typical water table is less than 4' below the original ground level

4.3.2.2 Work Item Level

The Work Item-level data collection tool was used to document the completed quantity of work, crew information, equipment information, total working days, as well as disruptions. A tracking calendar that was made a part of the Work Item-level data collection tool was created to track the information.

4.3.3 Work Item Sheets

Lack of standardization for measuring productivity is an obstacle for the comparison of construction productivity between projects (Borcherding and Alarcon 1991). A consistent data collection technology is required to study productivity in the construction industry (Sanders and Thomas 1991).

A Work Item sheet (Appendix E) was developed to guide data collectors to consistently document Production Rates. Each Work Item sheet includes item number, Work Item description, measured unit, scope of measurement, specific factors and crew definition for each Work Item. The scope of each Work Item was determined by the research team and PMC members. The start node, end node, in-scope activities, and out-scope activities were listed on each Work Item sheet. Notes on Work Item-specific Candidate Drivers were listed on the Work Item sheet to remind data collectors during the data collection process as well.

4.4 PILOT DATA COLLECTION

As the data collection tools were developed and the process was established, a pilot data collection effort was conducted to test if the data collection tools and planned process were effective. A TxDOT district was selected in which to perform the pilot data collection. Three construction projects with different levels of complexity were selected.

At the beginning of the pilot data collection, the research team concentrated their efforts on a simple project to collect Production Rate data. Two months after working on the first project, two construction projects that were more complicated were studied. A total of twelve data points were collected in the first district from late February to late July of 2002. The efficiency of the data collection was low because only one or two projects were studied concurrently and the targeted Work Items in the on-going projects were not performed according to the planned schedule. The data collection process then was adjusted to collect data on more than three construction projects simultaneously. Despite these difficulties encountered during the pilot data collection, the data collection tools were refined in such a way as to be more complete and efficient.

4.5 DATA COLLECTION

Project-level information was collected during the project meetings. Other information was collected at regular job visits. The scope of each targeted Work Item is presented in this section.

4.5.1 Excavation

Table 4.3 presents the scope of Excavation employed for data collection. The scope of Excavation starts with removing the soil or excavating for a construction phase and ends when the elevation of the sub-grade or the working phase is reached. The activities included in the scope are removing the top soil, excavating from the original elevation to the elevation of the sub-grade, loading excavated materials, and disposal of materials. The rock Excavation Operation was excluded.

Table 4.3 Scope of Excavation for Data Collection

<table>
<tr><th>SCOPE</th><th colspan="2">Included</th><th>Not Included</th></tr>
<tr><td colspan="3">- Removing top soil
- Excavation from original elevation to the elevation which is at least 6" below the required sub-grade elevation
- Disposal of material</td><td>- Survey & Layout
- Access road construction and maintenance
- Unsuitable material replacement
- Reshaped by blade and then sprinkled and rolled for sub-grade surface (about 6" depth)
- Temporary drainage maintenance
- Shaping slop
- Rock</td></tr>
<tr><td rowspan="2">NODE</td><td>Starting</td><td colspan="2">- Remove top soil.
- Starting the excavation of any working phase.</td></tr>
<tr><td>Ending</td><td colspan="2">- Sub-grade surface is completed.
- Reach the anticipated elevation of the working phase</td></tr>
</table>

In the construction industry, tracking the completed quantity in an Excavation Operation is a cumbersome task for clients and contractors. Contractors usually prefer to claim the completed quantity as large as possible to obtain higher payment on a unit price contract. In contrast, clients tend to pay for a completed quantity as low as possible to reduce the risk of overpayment. Therefore, an agreement between clients and contractors on the methods of tracking the excavated quantity should be made at the start of a construction project.

There are three methods of tracking the completed quantity for an Excavation Operation employed by TxDOT. First, the general contractor proposes a quantity report according to the quantity calculated from the numbers of loaded trucks, trailers, or scrapers. Based on the proposed quantity, TxDOT will approve or adjust the quantity depending on the planned quantity. This method is mostly applied to projects with a large amount of Excavation at a certain Work Area. Secondly, the general contractor proposes a quantity report based on the quantity calculated from the planned quantity. TxDOT will review the quantity report and then adjust or approve the quantity report. Thirdly, the general contractor and TxDOT evaluate the percentage of completion together and then calculate the completed quantity by multiplying the planned quantity and the percentage of completion. The completed quantity in the study was collected from TxDOT's approved quantity. The standard resource used in the Excavation Operation is one excavator with a 2 cubic yardage bucket and trucks.

4.5.2 Embankment

The scope of the Embankment Operation, shown in Table 4.4, starts from placing the first load of material in a working phase and ends by reaching the planned elevation. This is somewhat different than the scope described in TxDOT's construction specification, which starts from removing the top soil and ends by reaching the elevation of the sub-grade or the elevation instructed by the engineers. It is difficult to measure the Production Rate starting from the removal of the top soil until it reaches the elevation of the sub-grade. Since the sources of materials used in Embankment for a certain Work Area could be obtained from varied Work Areas or projects, the Embankment Operation is usually divided into multiple phases. The time intervals between two successive phases are varied and not predicable. The standard resource used in the Embankment Operation is one or two dozers and a compactor.

Table 4.4 Scope of Embankment for Data Collection

<table>
<tr><th>SCOPE</th><th colspan="2">Included</th><th>Not Included</th></tr>
<tr><td colspan="3">(Construction of roadway embankments, levees and dykes or any designated section of the roadway)
- Placing materials
- Spread material
- Sprinkling
- Compaction</td><td>- Survey & Layout
- Constructing access road
- Temporary drainage maintenance</td></tr>
<tr><td rowspan="2">NODE</td><td>Starting</td><td colspan="2">- Place the first load of embankment material.</td></tr>
<tr><td>Ending</td><td colspan="2">- Sub-grade surface is completed. .
- Reach the elevation of the working phase if there are more than one phases of embankment</td></tr>
</table>

4.5.3 Lime-Treated Sub-grade

Lime-treated sub-grade is a common method of stabilizing the sub-grade in Texas due to expansive soil. Adding lime to the soil can make it more flexible and thus reduces the possibility of cracking in the surface of sub-grade. Another advantage is to prevent the intrusion of water into the sub-grade. When the elevation of a sub-grade has been reached and compaction and grading have been completed, slurry or dry lime is placed on the sub-grade. A cutting and pulverizing machine is used to cut the sub-grade uniformly to a proper depth, usually six inches, and then the cutting material is mixed with the lime. After the mixing process, a motor grader, a sheep-foot roller and a steel roller are used to compact and seal the sub-grade. The above processes are called the "first mixing".

After the first mixing, the sub-grade is left to cure for one to four days depending on the decision of the TxDOT engineers. If a "Type C" lime is used, the sub-grade needs two to seven days for curing. The typical duration of the first curing in the observations is two days. After curing, the sub-grade is mixed again. This is the second mixing. This time the sub-grade is shaped to the required grade after mixing is completed. Following the second mixing, the sub-grade is cured again and then the Aggregate base course or pavement structure is placed on top of the sub-grade (TxDOT 1993).

The scope of Lime-treated sub-grade, shown in Table 4.5, starts with spreading lime for the first mixing and ends with finishing sub-grade surface. The second curing is excluded in the scope because of the high variation in its duration. The second curing varies from one day to fourteen days depending on the engineers' instruction or the contractor's working plan. The standard resource used in the Lime-treated sub-grade Operation is a mixer, a motor grader, a sheep-foot roller, a steel roller, one or two spreaders and a water truck.

Table 4.5 Scope of Lime-Treated Sub-grade for Data Collection

SCOPE	Included		Not Included
- Cutting & pulverizing - Spread Lime - Mixing - Sprinkling or aerating - Compaction - Finishing - 1^{ST} curing and 2^{nd} mixing			- Survey & layout - Equipment move in - Transport material - Curing (after finishing) - Density tests - Setup blue top
NODE	**Starting**	- Spread lime or cut & pulverize sub-grade.	
	Ending	- Finishing sub-grade surface is completed.	

4.5.4 Aggregate Base Course

Two types of Base course were observed in this study. The first type is the Flexible base course. Such a Base course usually contains multiple lifts. The observed thickness of a lift varies from three to six inches. This Work Item starts from hauling the flexible base material to the job site. Spreading and shaping is usually performed on the same day of hauling. Following that, processing, which includes compacting and finishing, is performed. Sometimes, the timing between processing and hauling is long because contractors wait for the sub-grade of another section to be complete so they can process the two sections together. After a Flexible base course is completed, it will be cured for about two days, as suggested by the TxDOT inspectors, before the surfacing will be placed on the completed Base.

The second type of Aggregate base course is the Cement-treated base (CTB) course. Two mixing methods are applied to the CTB: plant mixing and road mixing. No data for road mixing CTB was collected for this study, therefore only the CTB for plant mixing will be studied. In this type of Operation, the CTB material is delivered from the plant to the job site and then is placed and spread on the top of the sub-grade. Following that, the compaction is completed within two hours for each lift as there is limited duration on processing cement mixed material because of the interactions between the cement and water. If the CTB has multiple lifts, the compaction of all lifts must be completed within five hours (TxDOT 1993). The CTB Operation observed in this study was constructed in a single lift which had a uniform thickness of six inches. After the CTB was completed, it usually requires at least seventy two hours for curing.

The scope of the Aggregate base Operation, shown in Table 4.6, starts from delivering Base materials to the job site and ends at the completion of the Base course. Curing, material tests, and density tests were excluded in the scope.

The completed quantity of this Work Item was the area in which the contractors process an Aggregate base Operation. The unit measured in the study was Lift-SY/Crew Day. It refers to the number of square yards of a Base lift that is completed using a standard size of crew. The standard resource used in the Aggregate base Operation is a motor grader, one or two rollers and a water truck.

Table 4.6 Scope of Aggregate Base for Data Collection

<table>
<tr><th>SCOPE</th><th colspan="2">Included</th><th>Not Included</th></tr>
<tr><td colspan="3">- Placing materials
- Spread uniformly & shaping
- Blade & shaping
- Sprinkling
- Compaction
- Dry-out (if required)</td><td>- Survey & layout
- Shaping the sub-grade or existing roadbed
- Stockpiled
- All material tests excluded
- Curing (Flexible Base: Directed by Engineers, usually 2 days; CTB: 72 hours)
- Density tests
- Rework caused by failing to achieve required density</td></tr>
<tr><td rowspan="2">NODE</td><td>Starting</td><td colspan="2">- Place the first load of base material.</td></tr>
<tr><td>Ending</td><td colspan="2">- Finishing a lift of base course is completed.</td></tr>
</table>

4.5.5 Hot Mix Asphalt Pavement

Hot mix asphalt pavement (HMA) includes the construction of the HMA base and surface. Two types of HMA base were included in the scope. The first type is the HMA base constructed for use under Concrete pavement and the other type is constructed as the base course of the HMA surface.

The scope of an HMA Operation, shown in Table 4.7, includes transporting HMA materials, setting up the lay-down machine, placing HMA and compaction. The completed quantity is measured as tonnages of HMA placed on a targeted Work Area by a standard resource. The standard resource used in the Hot mix asphalt pavement is a lay-down machine, a pneumatic roller, a steel roller, and a finishing crew consisting of six to eight workers.

Table 4.7 Scope of Hot Mix Asphalt Pavement for Data Collection

SCOPE	Included	Not Included
	- Lay Hot Mix Asphalt - Compaction (Roller or lightly oiled tamps)	- Transport materials - Cleaning surface before applying for tack coat - Shoot tack coat (if tack coat required) - Survey and layout - Mixing materials in the plant - Equipment setup
NODE	**Starting**	- Place the first load of Hot Mix Asphalt material.
	Ending	- Complete compaction.

4.5.6 Slip-form Concrete Pavement

Two types of Slip-form concrete pavement Operations were observed in the study period. They include continuously reinforced concrete pavement (CRCP) and jointed concrete pavement (JCP). The difference between these two types is the usage of reinforced steel in the Concrete pavement. In this study, JCP was excluded because it is rarely used by TxDOT.

The scope of Slip-form concrete pavement, shown in Table 4.8, starts at the setting of the string line and ends at the finishing of the surface of Concrete pavement. For CRCP, it was found that there was often a long time after rebar installation and before concrete placement. This is because contractors can achieve better production by reducing the number of times for setting up the slip-form paver. The standard resource used in the Slip-form concrete pavement Operation is a slip-form paver, material-transfer equipment and a rebar crew consisting of eight to ten workers and a concrete crew consisting of six to eight workers.

Table 4.8 Scope of Slip-form Concrete Pavement for Data Collection

SCOPE		**Included**	**Not Included**
- Setting string line - Placing dowels - Installing reinforcing steel - Placing joint assemblies - Initial equipment setup - Placing concrete - Finishing			- Survey & Layout - Surface preparation - Equipments move in - Ride quality test - Core test - Unloading reinforcing steel - Curing - Saw cutting
NODE	**Starting**	- Set string line.	
	Ending	- Complete concrete placement.	

4.5.7 Conventional Form Concrete Pavement

Table 4.9 presents the scope of Conventional form concrete pavement employed for the data collection of this study. Conventional form concrete pavement starts with setting up formwork and ends at the completion of concrete placement. The standard resource used in Conventional form concrete pavement is a formwork crew with four to six workers, a rebar crew with six to ten workers, and a concrete crew with six to ten workers.

Table 4.9 Scope of Conventional Form Concrete Pavement for Data Collection

SCOPE		Included	Not Included
- Formwork - Installing reinforcing steel - Placing concrete - Spread and finishing -			- Survey & Layout - Surface preparation - Cutting & bending Reinforcing steel - Core test - Curing - Removing formwork
NODE	Starting	- Start to setup formwork	
	Ending	- Complete concrete placement.	

4.6 Summary of Study Districts and Projects

A total of thirty-five on-going projects from seven districts were investigated for this study. The visited districts and their respective number of visited projects are listed in Table 4.10. Among the seven districts, three were located in Central and South Texas, two were in the coastal region, and one each in North

Texas and the Panhandle and West Texas. General project information for the study projects is presented in Appendix G. Production Rate data in this study were collected from early March, 2002 to late March, 2004. A total of 196 data points were collected.

Table 4.10 Dates of Collecting Data, Number of Investigated Projects and Number of Observed Data by Visited Districts

Visited Districts	Area	Dates of Collecting Data	Total number of Projects	No. of Observed Data	
				Total Number of Work Items	Total Data Points
D1	Central and South Texas	3/1/02 ~ 7/31/02	4	5	13
D2	Coastal Texas	7/1/02 ~ 9/1/02	2	2	13
D3	Central and South Texas	9/1/02 ~ 2/10/03	4	5	34
D4	North Texas	11/7/02 ~ 2/25/03	7	7	33
D5	Coastal Texas	3/20/03 ~ 11/1/03	9	7	68
D6	Panhandle and West Texas	9/16/03 ~ 11/1/03	2	3	10
D7	Central and South Texas	11/15/03~3/31/04	7	6	25
	Total		35		196

Twenty-two different contractors built these projects, as shown in Table 4.11. The average ratio of observed projects versus prime contractors is 1.5. Table 4.12 displays the number of projects according to contract amount. Most of the projects had a contract amount of less than thirty million dollars. Only two projects had a contract amount of more than one hundred million.

Table 4.11 Number of Projects by Prime Contractor I.D.

Contractors	Number of Projects	Contractors	Number of Projects
GC1	1	GC12	1
GC2	1	GC13	1
GC3	1	GC14	2
GC4	2	GC15	1
GC5	2	GC16	1
GC6	2	GC17	1
GC7	1	GC18	1
GC8	1	GC19	2
GC9	1	GC20	5
GC10	1	GC21	1
GC11	1	GC22	5
Total			**35**

Table 4.12 Number of Projects by Contract Amount

Contract Amount (Million)	Number of Projects
0 ~ 9.99	14
10 ~ 19.99	8
20 ~ 29.99	5
30 ~ 39.99	1
40 ~ 49.99	1
50 ~ 59.99	1
60 ~ 69.99	0
70 ~ 79.99	1
80 ~ 89.99	2
90 ~ 99.99	0
>100	2
Total	**35**

4.7 SUMMARY OF PRODUCTION RATE DATA

A tabular summary of data observations for each Work Item is listed in Table 4.13. Production Rates for each Work Item were collected at a wide variety of projects in several districts. Several different prime contractors were observed, so biases due to region and contractor would be limited.

Table 4.13 Sources for Data and Observed Quantity for Seven Work Items

Work Item	Number of Data Points	Number of Districts	Number of Projects	Number of Prime Contractors	Total of Observed Quantity
Excavation	26	5	12	10	154,570 CY
Embankment	34	5	16	12	237,415 CY
Lime-treated Sub-grade	32	6	18	12	317,235 SY
Aggregate Base Course	29	6	15	13	414,826 SY-LIFT
Hot Mix Asphalt Pavement	32	6	19	14	61,152 TON
Slip-form Concrete Pavement	23	3	10	6	169,357 SY
Conventional Form Concrete Pavement	20	4	8	5	21,889 SY

CHAPTER V: DESCRIPTIVE STATISTICS OF OBSERVED PRODUCTION RATES

A survey conducted in January 2003 indicated that most TxDOT districts considered the Production Rates of CTDS to be unrealistic and in need of revision. In addition, most members of the PMC believed that the Production Rates for Earthwork and Pavement construction were too optimistic. Box plots are used herein to compare the Production Rates of the observed data, CTDS, and historical records. Table 5.1 displays the range as well as the mean of the observed Production Rates for each Work Item.

Table 5.1 Range Data for Seven Work Items

Work Item	Unit	Minimum	Mean	Maximum
Excavation	CY/Crew Day	199	1163	3558
Embankment	CY/Crew Day	249	1097	3000
Lime-treated Sub-grade	SY/Crew Day	82	1563	3722
Aggregate Base Course	SY-Lift/Crew Day	526	3398	6500
Hot Mix Asphalt Pavement	TON/Crew Day	158	817	1460
Slip-form Concrete Pavement	SY/Crew Day	462	1253	2154
Conventioinal Form Concrete Pavement	SY/Crew Day	30	306	582

Other existing Production Rate sources such as the *Caterpillar Performance Handbook* which documents the Production Rates of each piece of caterpillar equipment are not applicable for comparison. This study was more concerned about the Production Rates of Operations, which usually combine the work of several pieces of equipment and/or labors, rather than the Production Rates of a single machine.

5.1 Excavation

Figure 5.1 displays data summaries for comparison of Production Rates from different sources of Excavation. Production Rate data were observed directly from twelve projects in five districts in Texas. The average observed Production Rate was 1,163 CY/Crew Day, which is much slower than the average CTDS rate, 3,400 CY/Crew Day, but faster than the Production Rates found in most of the historical records. Almost no information is available to further explore the causes of lower Excavation Production Rates for historical data.

Data Source	No. Districts	No. Projects	No. Data Points	No. CY
Observations	5	12	26	154,570
CTDS	N/A	N/A	N/A	N/A
As-Built 1	1 (D3)	1	129	175,556
As-Built 2	1 (D3)	1	456	327,394
As-Built 3	1 (D4)	1	23	4,910
As-Built 4	1 (D4)	1	250	87,832
As-Built Projects	1 (D8)	11	126	89,819

Unit: CY/Crew Day

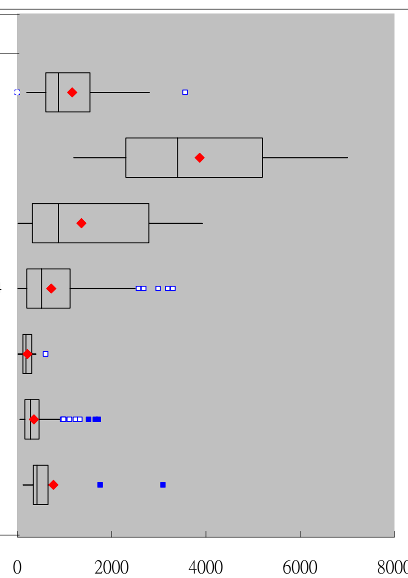


Figure 5.1 Comparison of Excavation Production Rates from Different Sources

5.2 Embankment

Figure 5.2 presents the distribution of Production Rates among different sources for Embankment. Production Rate data were collected from sixteen projects in five districts in Texas by direct observation. The average observed Production Rate was 1,097 CY/Crew Day, which is much slower than the average CTDS rate of 3,500 CY/Crew Day. The observed Production Rates were close to the Production Rates in As-built 2 and As-built 4 and faster than other as-built rates.

Data Source	No. Districts	No. Projects	No. Data Points	No. CY
Observations	5	16	34	237,415
CTDS	N/A	N/A	N/A	N/A
As-Built 1	1 (D3)	1	22	13,683
As-Built 2	1 (D3)	1	543	688,520
As-Built 3	1 (D4)	1	16	4,272
As-Built 4	1 (D4)	1	197	190,436
As-Built Projects	1 (D8)	10	125	52,285

Unit: CY/Crew Day

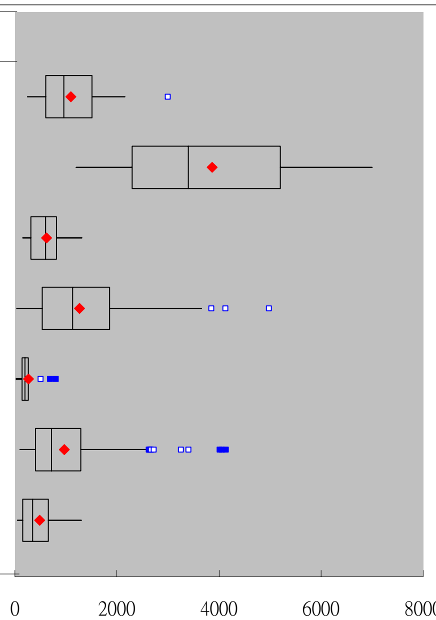


Figure 5.2 Comparison of Embankment Production Rates from Different Sources

5.3 Lime-Treated Sub-grade

Figure 5.3 shows the distribution of Production Rates obtained from different sources for Lime-treated sub-grade. Thirty-two data points were observed from eighteen projects in six districts. The work scope included in the Production Rates for CTDS and RS Means is different than that for this study and As-built rates. For CTDS and RS Means, the first curing is excluded; however first curing is included in the rates for this study and As-built rates. Therefore, for comparison purposes only, observed Production Rates were computed excluding the first curing and plotted in Fig 5.3.

Data Source	No. Districts	No. Projects	No. Data Points	No. SY
Observations (1st Curing included)	6	18	32	317,235
Observations (1st Curing excluded)	6	18	32	317,235
CTDS (1st Curing excluded)	N/A	N/A	N/A	N/A
As-Built 1	1 (D3)	1	5	19,125
As-Built 2	1 (D3)	1	0	0
As-Built 3	1 (D4)	1	4	6,552
As-Built 4	1 (D4)	1	20	53,250

Unit: SY/Crew Day

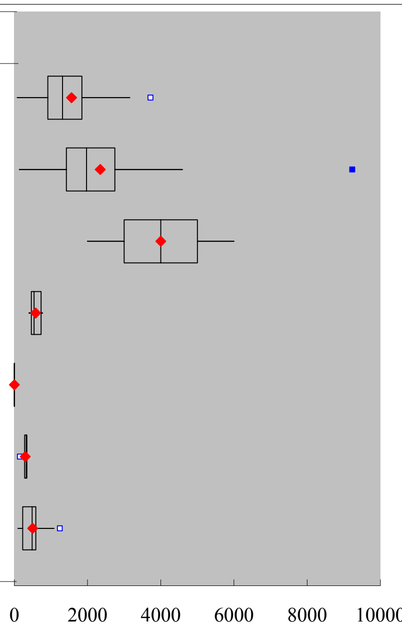


Figure 5.3 Comparison of Lime-Treated Sub-grade Production Rates from Different Sources

The average CTDS Production Rate is 4,000 SY/Crew Day. The average observed Production Rate, including the first curing, was 1,563 SY/Crew Day, and 2,348 SY/Crew Day excluding the first curing.

5.4 Aggregate Base Course

Figure 5.4 presents a comparison of Production Rates collected from this study and those retrieved from the CTDS for Aggregate base course. No historical records were used for this comparison because it was difficult to identify the working days for processing Aggregate base from such records. Due to the different working process between Cement-Treated Base (CTB) and Flexible base, the observed Production Rates were separated into two groups for better comparison.

Fourteen data points from six projects in one district were collected for CTB, with a total quantity of 157,308 LIFT-SY. For Flexible base course, fifteen data points from nine projects in five districts were collected with a total of 257,518 LIFT-SY. The average observed Production Rate was 4,050 LIFT-SY/Crew Day for CTB and 2,788 LIFT-SY/Crew Day for Flexible base course. The average CTDS Production Rate for both CTB and Flexible base is 3,000 LIFT-SY/Crew Day. Therefore, the CTDS Production Rate of CTB is much lower than the average observed rate. In contrast, the average CTDS Production Rate for Flexible base is higher than that from field observations.

Data Source	No. Districts	No. Projects	No. Data Points	No. SY-LIFT
Observations (Cem. T. Base)	1	6	14	157,308
Observations (Flex. Base)	5	9	15	257,518
CTDS (Cem. T. Base)	N/A	N/A	N/A	N/A
CTDS (Flex. Base)	N/A	N/A	N/A	N/A

Unit: SY-LIFT/Crew Day

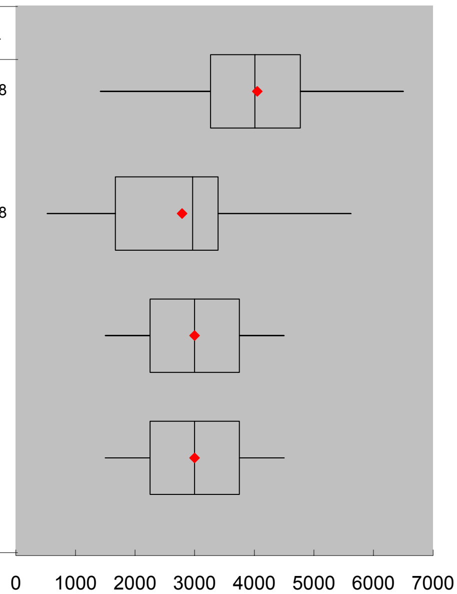


Figure 5.4 Comparison of Aggregate Base Course Production Rates from Different Sources

5.5 Hot Mix Asphalt Pavement

Figure 5.5 presents side-by-side box plots of Production Rates of Hot mix asphalt (HMA) pavement collected from different sources. Thirty-two data points were observed for Hot mix asphalt pavement. Nineteen projects in six districts were investigated with a total of 61,152 tons of HMA placed. The average CTDS Production Rate for HMA pavement is 1,200 Tons/Crew Day. The average observed Production Rate fell between the average CTDS rate and the average rates from historical records.

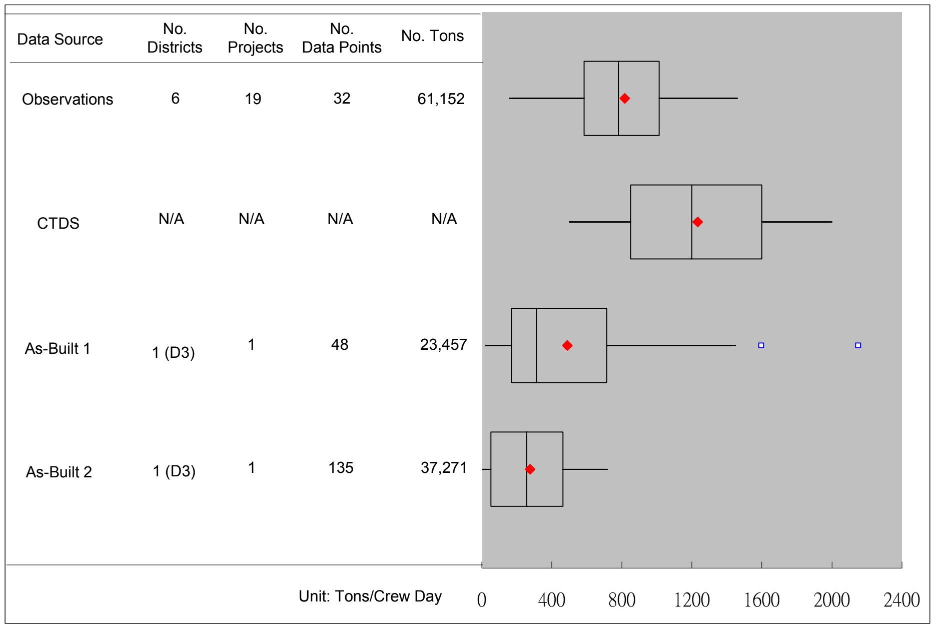


Figure 5.5 Comparison of Hot Mix Asphalt Pavement Production Rates from Different Sources

5.6 Slip-form Concrete Pavement

Figure 5.6 displays side-by-side box plots of Production Rates from observations, as-built projects, and CTDS. The Production Rates of twenty-three Work Zones from ten projects in three districts were investigated. Of those data points, three were Jointed Concrete Pavement (JCP). The others were for Continuously Reinforced Concrete Pavement (CRCP). A total of 161,133 square yards of CRCP Operations and 8,224 square yards of JCP were observed. The Production Rate of CRCP is much lower than JCP because JCP does not involve time-intensive rebar work.

The average Production Rate of the observed CRCP Operations was 1,357 SY/Crew Day, which was faster than the average Production Rate of the As-built project 4 but much slower than the average CTDS Production Rate of 3,000 SY/Crew Day. The observed Production Rate of JCP Operations was 1,729 SY/Crew Day, which is relatively close to the average rate of the As-built project 3.

Data Source	No. Districts	No. Projects	No. Data Points	No. SY
Observations (JCP)	1	1	3	8,224
Observations (CRCP)	3	9	20	161,133
CTDS	N/A	N/A	N/A	N/A
As-Built 3 (JCP)	1 (D4)	1	19	22,617
As-Built 4 (CRCP)	1 (D4)	1	1	342

Unit: SY/Crew Day

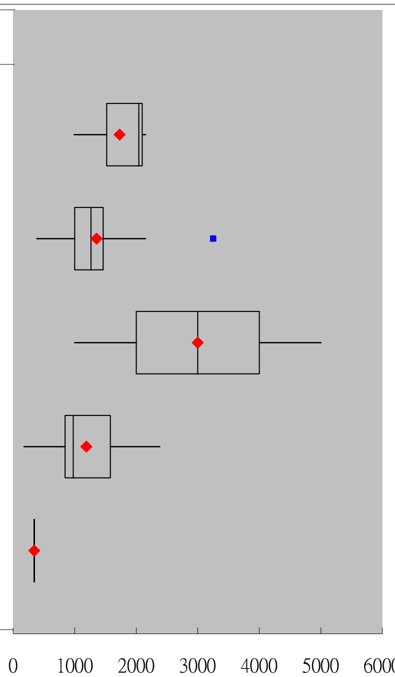


Figure 5.6 Comparison of Slip-form Concrete Pavement Production Rates from Different Sources

5.7 Conventional Form Concrete Pavement

Figure 5.7 displays observed Production Rates and three as-built projects for Conventional from concrete pavement. A total of 20,944 square yards of

Concrete pavement construction were observed. The average observed Production Rate was 338 SY/Crew Day. The range of observed Production Rates is similar to the range obtained from the As-built projects.

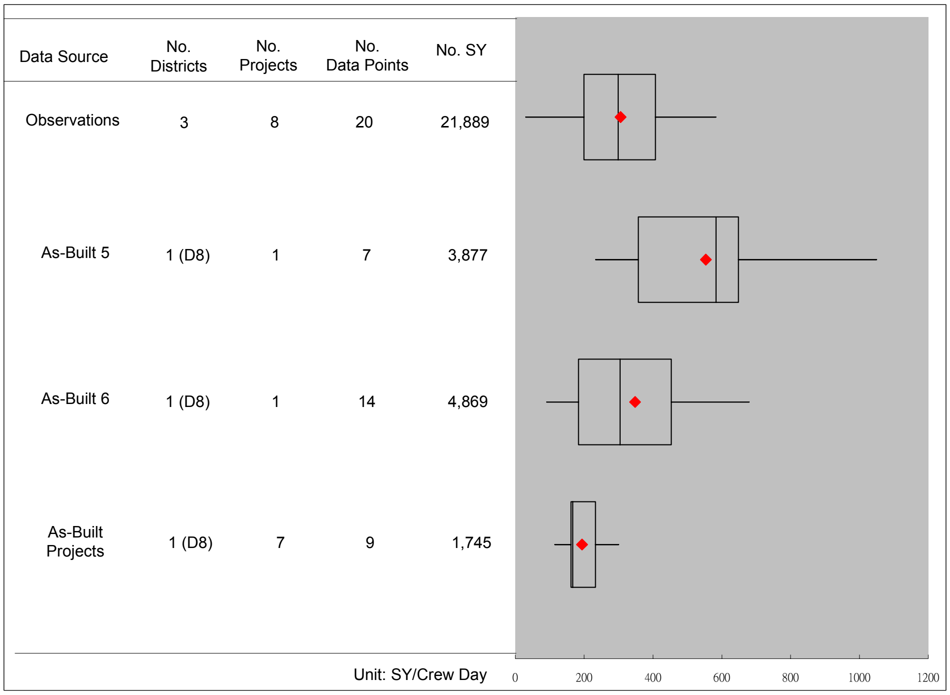


Figure 5.7 Comparison of Conventional Form Concrete Pavement Production Rates from Different Sources

CHAPTER VI: DATA ANALYSIS AND HYPOTHESIS TESTING FOR EARTHWORK-RELATED WORK ITEMS

The ANOVA/t test was employed to test if there were different mean Production Rates within groups for drivers involving categorical or discrete numerical data. A non-linear or linear regression analysis was employed to explore the relationships between Production Rates and drivers. This was applied for drivers involving continuously numerical data. The logarithmic model and the power model were used to identify non-linear relationships of Production Rates and drivers. For each factor analysis, the R-squares and the adjusted R-square of the linear, logarithmic, and power models were examined. The assumptions of each model were examined in order to determine the best model for studying the effects of the driver on the Production Rates of the targeted Work Item.

When the regression analysis was employed to analyze the effects of drivers on Production Rates, outliers of each variable were identified and removed from the data set (shown in Appendix H). A linear or non-linear model was employed to study the effects of drivers and then the violations of the assumptions of the regression analysis were checked.

6.1 TEST DIFFERENCE IN MEAN PRODUCTION RATES

Mean observed Production Rates were compared with average CTDS rates to test the first hypothesis which is presented as follows:

Hypothesis 1: The Production Rates of the CTDS are not realistic.

The established null hypothesis is that the mean observed Production Rates are equivalent to the average CTDS rates for major Work Items of Earthwork construction. In other words, the established alternative hypothesis is that average CTDS Production Rates are different from mean observed Production Rates.

The results of the hypothesis testing are displayed in Table 6.1. Except for Flexible base, other Work Items show that there is a significant difference between the average rate of the CTDS and the mean observed Production Rates. As clearly indicated, the Production Rates of the CTDS are too optimistic for Excavation, Embankment and Lime-treated sub-grade. The average Production Rate of the CTDS for Cement-treated base is slower than the mean observed Production Rate, however.

Table 6.1 Average Production Rates of the CTDS and Mean Observed Production Rates

Work Item	Number of Data Points	Unit	Mean Observed Production Rate	Average CTDS Rate	Mean Difference	P-Value
Excavation	26	CY/Crew Day	1163	3400	-2237	*0.000
Embankment	34	CY/Crew Day	1097	3500	-2403	*0.000
Lime-Treated Sub-grade	32	SY/Crew Day	2348	4000	-1652	*0.000
Flexible Base Course	15	SY-Lift/Crew Day	2788	3000	-212	0.583
Cement Treated Base	14	SY-Lift/Crew Day	4050	3000	1050	*0.013

* indicates that P-value is less than 0.05 and thus, the null hypothesis (Mean Observed Production Rate = Average CTDS Rate) is rejected at 95% confidence interval.

6.2 ANALYSIS OF DRIVERS OF PRODUCTION RATES

Several Candidate Drivers were selected in Section 4.1 and further investigated for their effects on Production Rates. The following is the formulation of the second hypothesis.

Hypothesis 2: The Production Rates of the targeted Work Items are driven by some productivity factors that are known at the design stage.

6.2.1 Excavation

Scatter plots, shown in Appendix I-1, were used to examine the relationship between twelve Candidate Drivers and Excavation Production Rates. All but Work Area Quantity were excluded from further driver analysis as the observed Production Rates did not exhibit any specific relationship to the variability of Candidate Drivers. Figure 6.1 displays the scatter plot of observed Production Rates versus Work Area Quantity. A possible non-linear or linear relationship of Work Area Quantity and Production Rates can be observed from the scatter plot. The sub-hypotheses of the second hypothesis, listed as follows, were further tested for Excavation.

Sub-hypothesis 1: Operations and resource allocation will be more efficient when the amount of repetitive work in a Work Area is great. More resources may be used to amplify daily Production Rates. This may be true for Excavation because its Operations are highly repetitive. In addition, productive hours in a working day may be higher for the Work Area with greater quantity.

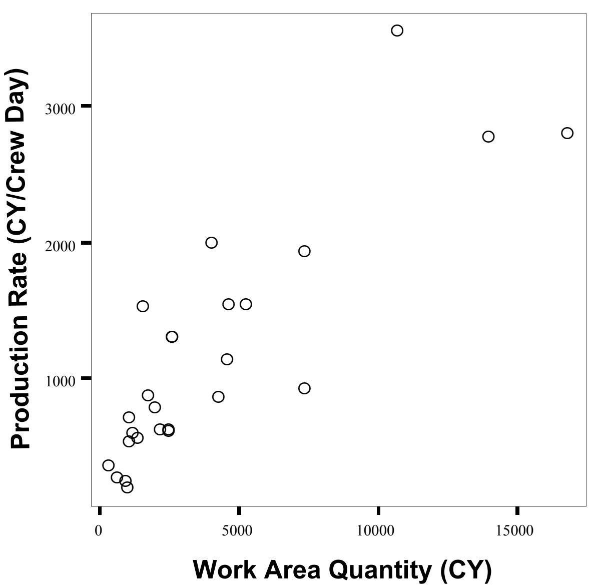


Figure 6.1 Scatter Plot for Excavation: Observed Production Rates (CY/Crew Day) and Work Area Quantity (CY)

Excavation: Observed Production Rates and Work Area Quantity

The logarithmic model was found to be the most efficient model for the relationship between observed Production Rates and Work Area Quantity for Excavation among three selected models (linear model, logarithmic model and power model). Prior to using the logarithmic model, the box plots of the dependent variable (i.e. the observed Production Rate) and the independent variable (i.e. the logarithmic transformation of Work Area Quantity), shown in Figure 6.2 and Figure 6.3 respectively, were employed for outlier analysis. The seventh data point was found to be an outlier. This outlier was removed before conducting further regression analysis. The fitted logarithmic model, which was used to explore the relationships between the observed Production Rates and the Work Area Quantity for Excavation construction, is shown in Figure 6.4.

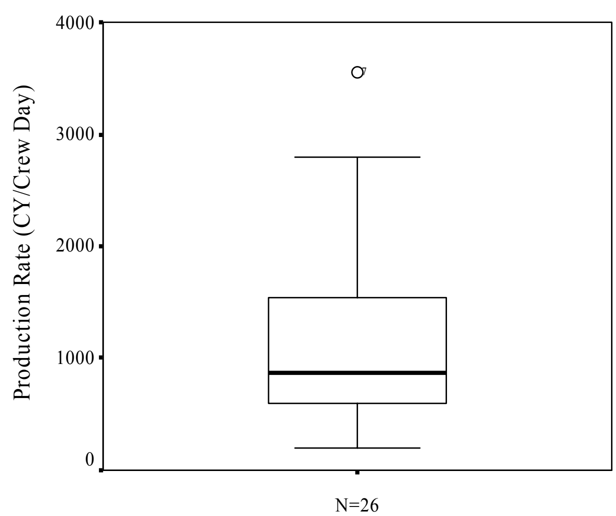


Figure 6.2 Excavation: Box Plot of Observed Production Rates (CY/Crew Day)

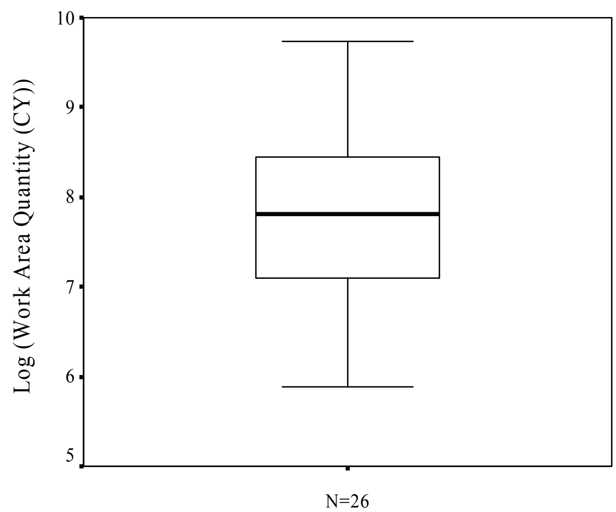


Figure 6.3 Excavation: Box Plot of Logarithmic Transformation of Work Area Quantity (CY)

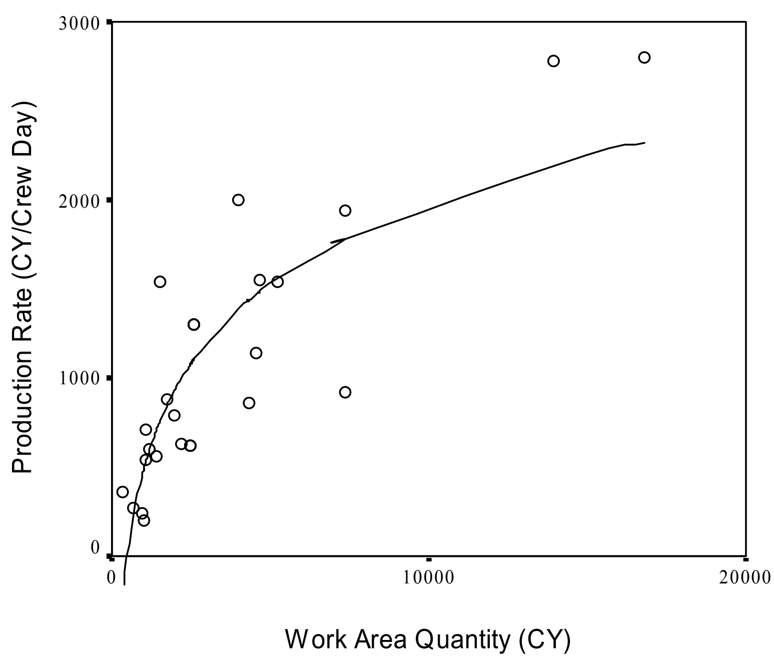


Figure 6.4 Scatter Plot and Fitted Logarithmic Model for Excavation: Observed Production Rates (CY/Crew Day) vs. Work Area Quantity (CY)

This model, shown as Equation 6.1, was statistically significant at the 95% confidence interval. Table 6.2 displays the results of a regression analysis using the logarithmic model. The R^2 and adjusted R^2 are 0.692 and 0.678 respectively. The coefficients of this model were statistically different from zero at the 95% confidence interval since the P-values were less than 0.05.

Production Rate = -3995 + 649 × Log (Work Area Quantity) (Equation 6.1)

Table 6.2 Logarithmic Model for Excavation: Production Rates (CY/Crew Day) by Work Area Quantity (CY)

R2		0.692
Adjusted R2		0.678
Standard Error		411
	F	P value
Regression Model	51.64	0.0000
Variable	B	P value
Work Area Quantity	649	0.0000
(Constant)	-3995	0.0000

Further tests were performed on the fitted logarithmic model to find violations of the assumptions of the regression analysis. The plots used to check for this are displayed in Appendix J. No violation of the assumptions was found as the plots show. Therefore, this model is statistically significant.

This fitted model is only applicable to Work Area quantities within the range of 472 CY to 16,798 CY since this model was developed based on observed data within that range. The predicted Production Rate will be negative if the Work Area Quantity is less than 472 CY, using this model. Therefore, the estimated Production Rates of this model can range from 199 CY/Crew Day to 2,319 CY/Crew Day. When the estimated Production Rate is less than 199 CY/Crew Day, the minimum observed Production Rate, 199, may be more reasonable than the predicted value. The effects of Work Area Quantity on the Production Rates of Excavation can be computed by differentiation, as shown in the Equation 6.2, of the fitted logarithmic model. Therefore, if two Work Areas have a quantity of Excavation close to 10,000 CY but different by 1,000CY, they may have a difference of about 65 CY/Crew Day in their average Production Rate.

$$\frac{\mathbf{d(Production\ \ Rate)}}{\mathbf{d(Work\ \ Area\ \ Quantity)}} = \frac{\mathbf{649}}{\mathbf{Work\ \ Area\ \ Quantity}} \quad \text{(Equation 6.2)}$$

Contractors tend to use a larger size of loading resources when the excavation quantity for a Work Area increases. The research identifies that the three types of loading machines that were commonly used for the excavation Operations: excavators, loaders and scrapers. Table 6.3 lists the types of loading machines found during the observations and the daily Production Rates of each machine published in the *Heavy Construction Cost Data* of RS Means 2002.

Table 6.3 Daily Production Rates (CY/Day) of Different Loading Machine (Adopted from *Heavy Construction Cost Data* of RS Means 2002)

Loading Machine	Daily Production Rate (RS Means)
Scraper (21CY, 1,500' Haul Distance)	1,030CY/DAY
Scraper (14CY, 1,500' Haul Distance)	800CY/DAY
Scraper (14CY, 3,000' Haul Distance)	700CY/DAY
Scraper (21CY, 5,000' Haul Distance)	650CY/DAY
Scraper (14CY, 5,000' Haul Distance)	560CY/DAY
Excavator (2CY Cap)	1,040CY/DAY
Excavator (1-1/2CY Cap)	800CY/DAY
Loader (Track, 3CY Cap)	1,040CY/DAY
Loader (Wheel, 2-1/4CY Cap)	800CY/DAY
Loader (Track, 2-1/2CY Cap)	760CY/DAY

However, as mentioned before, the resources used in different Operations vary. The daily Production Rate of 1,040 CY/Day using an excavator with 2CY bucket as listed in RS Means 2002 is treated as the standard resource. In order to study the relationship between size of loading resources and Work Area Quantity, the size of loading resources of each observed excavation data point was computed based on the suggested daily Production Rates in Table 6.3. For example, when two 14 CY scrapers with a 3000' haul distance and one 2-1/4 CY wheel loader are used, the size of loading resources is equivalent to 800+2*(700))/1040 = 2.12.

Figure 6.5 shows the relationship between observed Work Area Quantity and Size of an employed loading crew. A linear relationship with R^2 of 0.56 was found for the Work Area Quantity and the Size of resources.

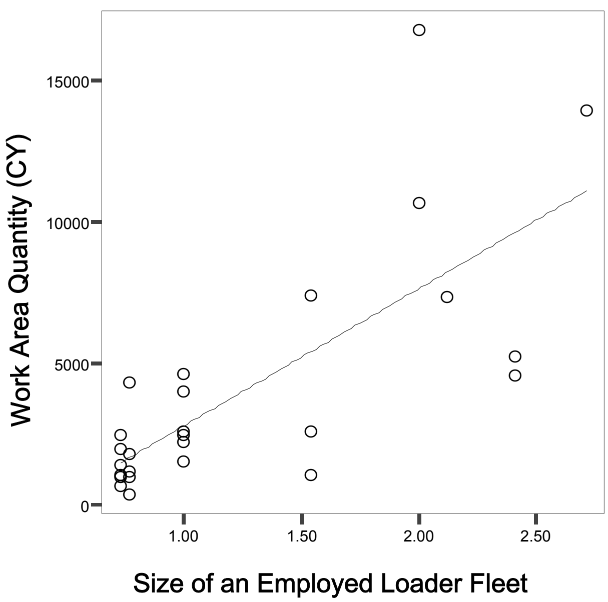


Figure 6.5 Scatter Plot and Fitted Linear Model for Excavation: Observed Work Area Quantity (CY) vs. Size of an Employed Loader Fleet

In addition, the observed Production Rates were standardized by the size of the loading resources for driver analyses. The scatter plots, shown in Appendix I-2, were used to examine the relationship between the twelve Candidate Drivers and the standardized Production Rates of Excavation. No statistically significant relationship was found in those plots.

6.2.2 Embankment

The scatter plots, shown in Appendix K, were used to examine the relationships of twelve Candidate Drivers on the Production Rates for Embankment. A non-linear relationship for Work Area Quantity and a difference in mean Production Rates for Work Zone accessibility and Work Zone congestion were observed. The scatter plots of those three Candidate Drivers are shown in Figure 6.6, Figure 6.7 and Figure 6.8. Other Candidate Drivers were excluded from further driver analysis. Three sub-hypotheses, listed as follows, were further tested for Embankment.

Sub-hypothesis 1: Based on the fact that repetition usually leads to greater efficiency and better resource allocation, Embankment Operations may be more productive in larger Operations. In addition, productive hours in a working day may be higher for the Work Area with larger quantity.

Sub-hypothesis 2: Work Zone congestion is negatively related to Production Rate. This assumption is made as it was observed that less congested Work Zones may allow more pieces of machinery to work simultaneously leading to higher Production Rates.

Sub-hypothesis 3: Work Zone accessibility has a significant impact on Production Rate. This is based on the assumption that higher Production Rate is possible if haul distance is short and the haul road condition is good.

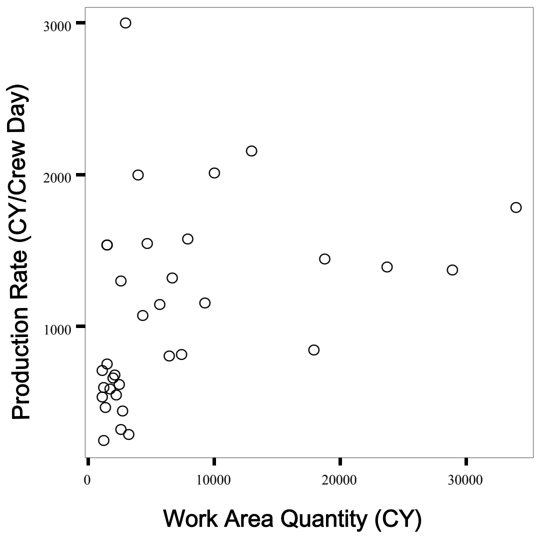


Figure 6.6 Scatter Plot for Embankment: Observed Production Rate (CY/Crew Day) vs. Work Area Quantity (CY)

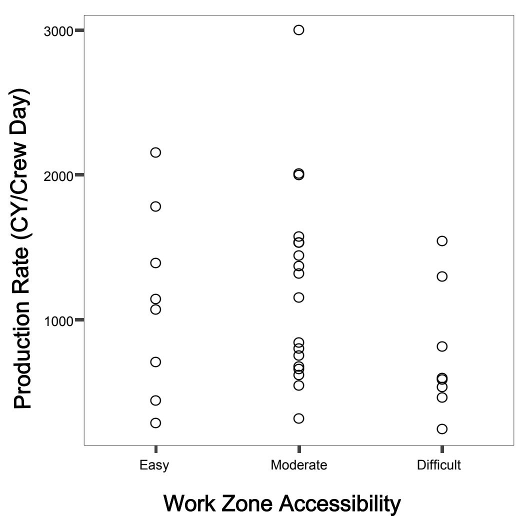


Figure 6.7 Scatter Plot for Embankment: Observed Production Rate (CY/Crew Day) vs. Work Zone Accessibility

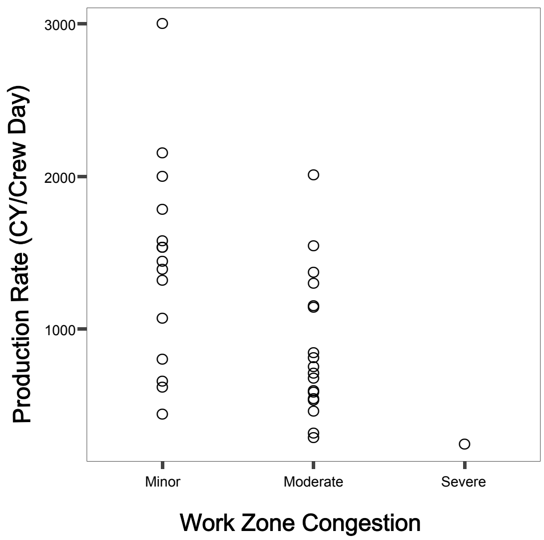


Figure 6.8 Scatter Plot for Embankment: Observed Production Rate (CY/Crew Day) vs. Work Zone Congestion

6.2.2.1 Embankment: Observed Production Rates and Work Area Quantity

The logarithmic model was found to be the most efficient model for the relationship between observed Production Rates and Work Area Quantity for Embankment. Prior to using the logarithmic model to identify the relationships, the box plots of the dependent variable (i.e. the observed Production Rate) and the independent variable (i.e. the logarithmic transformation of Work Area Quantity), shown in Figure 6.9 and Figure 6.10, were employed for outlier analysis. One data point was found to be an outlier and was removed before conducting further regression analysis. The fitted logarithmic model, which was used to explore the relationships between the observed Production Rates and Work Area Quantity for Embankment, is shown in Figure 6.11.

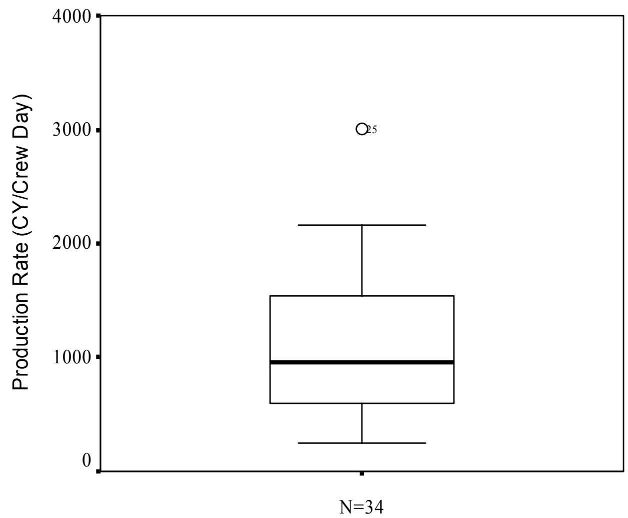


Figure 6.9 Embankment: Box Plot of Observed Production Rates (CY/Crew Day)

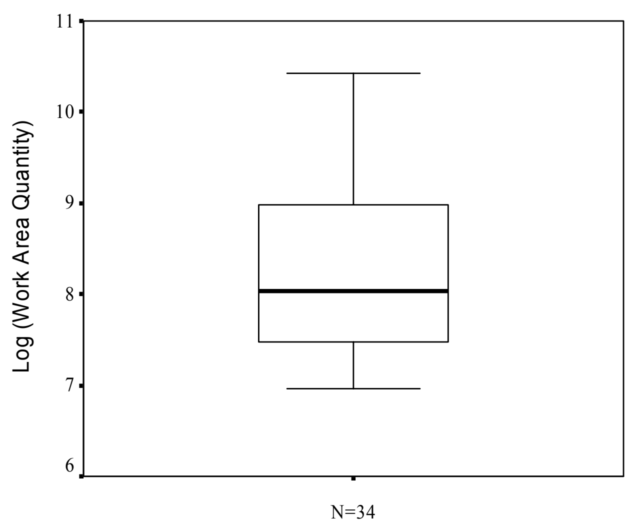


Figure 6.10 Embankment: Box Plots of Log (Work Area Quantity (CY))

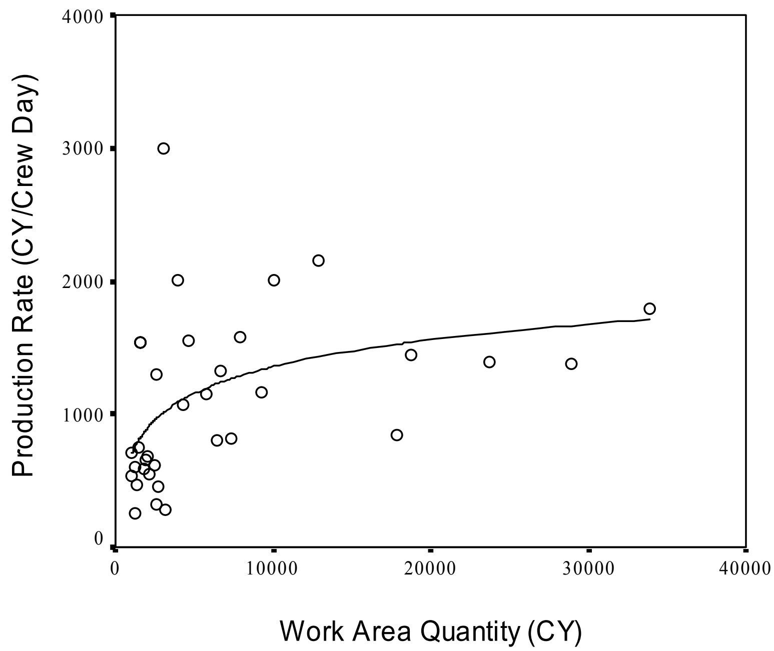


Figure 6.11 Scatter Plot and Fitted Logarithmic Model for Embankment: Observed Production Rates (CY/Crew Day) vs. Work Area Quantity (CY)

This model, shown as Equation 6.3, was statistically significant at the 95% confidence interval. Table 6.4 displays the results of the regression analysis using the logarithmic model. The R^2 and adjusted R^2 are 0.343 and 0.322 respectively. The coefficients of this model were statistically different from zero at the 95% confidence interval since the P-values of testing coefficients for Work Area Quantity and constant were less than 0.05.

Production Rate = -1531 + 309 × Log (Work Area Quantity) (Equation 6.3)

Table 6.4 Logarithmic Model for Embankment: Production Rates (CY/Crew Day) by Work Area Quantity (CY)

R2		0.343
Adjusted R2		0.322
Standard Error		444.99
	F	P value
Regression Model	16.2	0.0003
Variable	B	P value
Work Area Quantity	308.8	0.0003
(Constant)	-1530.9	0.0237

Next, tests to catch violations of the assumptions of the regression analysis were performed. The plots are displayed in Appendix L-1. No violation was found, as these plots exhibited. Thus, this model is statistically significant.

This model is only applicable to Work Area quantities within the range of 1,064 CY to 33,938 CY since this model was developed on this range. Therefore, the estimated Production Rates of this model can range from 621 CY/Crew Day to 1,691 CY/Crew Day. The effects of the Work Area Quantity can be computed by the differentiation of the fitted logarithmic model, as shown in Equation 6.4. Therefore, when two Work Areas have the quantity of Embankment Operations close to 10,000 CY but differ by 1,000 CY they may exhibit the difference of about 30 CY/Crew Day in their average Production Rate.

$$\frac{\mathbf{d(Production\ \ Rate)}}{\mathbf{d(Work\ \ Area\ \ Quantity)}} = \frac{\mathbf{309}}{\mathbf{Work\ \ Area\ \ Quantity}} \quad \text{(Equation 6.4)}$$

6.2.2.2 Embankment: Observed Production Rates and Work Zone accessibility

The number of data points collected for easy, moderate and difficult Work Zone accessibility was respectively 8, 18, and 8. The equality of variances of the three levels was tested by the homogeneity of variance test. Table 6.5 shows the results of the group variances test and the ANOVA test. The P-value of 0.503 indicated that the variances of the observed Production Rates in the three levels are statistically equal. ANOVA was then employed to test the difference in mean Production Rate for the three levels of Work Zone accessibility. The P-value of the ANOVA test was 0.215, which is greater than 0.05. According to the results, it can be concluded that the three levels did not have different mean Production Rates at the 95% confidence interval. With this limited data sample, this suggested that Work Zone accessibility is not a driver of Production Rates for Embankment. In addition, Table 6.6 presents the number of data points and mean Embankment Production Rate for the three levels of Work Zone accessibility. The average Production Rate in the Work Zone with moderate accessibility was higher than with easy accessibility. Therefore, it appears that Work Zone accessibility does not have a huge influence on Embankment.

Table 6.5 Results of Group Variances Test and ANOVA Test for Embankment: Work Zone Accessibility

Homogeneity of Group Variances Test	
	P value
Test Equality of Group Variances	0.503

ANOVA Test	
	P value
Test Equality of Means among Groups	0.215

Table 6.6 Numbers of Observed Data Points and Mean Production Rate for Embankment: Work Zone Accessibility

	Number of Data Points	Mean Production Rate (CY/Crew Day)
Easy Accessibility	8	1124
Moderate Accessibility	18	1233
Difficult Accessibility	8	762

6.2.2.3 Embankment: Observed Production Rates and Work Zone congestion

The number of data points collected for the three levels of Work Zone congestion; minor, moderate and severe, were 15, 18, and 1 respectively. As only one data point was available for severe congestion, it was excluded from the driver analysis. The t-test was employed to test the difference in mean Production Rate between minor and moderate Work Zone congestion, since the two levels are independent and normally distributed, as shown in Appendix L-2.

Table 6.7 presents the results of group variances test and t-test for the two levels. A P-value of 0.34 in the group variances test indicated that the two levels had equal variances at the 95% confidence interval. Based on the equal variances, the P-value of the t-test was found to be 0.009, which is less than 0.05. Therefore, the average Production Rate in Work Zones with minor congestion *is* significantly different than that with moderate congestion.

Table 6.8 indicates that the average Production Rate in the Work Zone is 1,424 CY/Crew Day with minor congestion and 872 CY/Crew Day with moderate congestion. The difference between the two levels is 552 CY/Crew Day.

Table 6.7 Results of Group Variances Test and ANOVA Test for Embankment: Work Zone Congestion

Homogeneity of Group Variances Test	
	P value
Test Equality of Group Variances	0.34

ANOVA Test	
	P value
Test Equality of Means among Groups	0.009

Table 6.8 Numbers of Observed Data Points and Mean Production Rate for Embankment: Work Zone Congestion

	Number of Data Points	Mean Production Rate (CY/Crew Day)
Minor Congestion	15	1424
Moderate Congestion	18	872

6.2.3 Lime-Treated Sub-grade

The scatter plots, shown in Appendix M, were used to examine the relationships of fourteen Candidate Drivers and observed Production Rates of Lime-treated sub-grade. Relationships for Work Area Quantity, Length of Work Area, and Location were observed. These scatter plots are shown in Figures 6.12, 6.13 and 6.14 respectively. Three sub-hypotheses, listed as follows, were tested for Lime-treated sub-grade.

Sub-hypothesis 1: Based on the fact that repetitive work leads to more efficient work Operations and resource allocation, Lime-treated sub-grade may be more efficient at higher quantities. In addition, productive hours in a working day may be higher for the Work Area with larger quantity.

Sub-hypothesis 2: For Lime-treated sub-grade, the longer the Length of a Work Area the more the number of repetitions there will be. When repetitions increase, the work will be more efficient due to learning effects.

Sub-hypothesis 3: Denser population and traffic will cause the work of Lime-treated sub-grade to be more dispersed. Dispersion of work has a negative relationship with productivity.

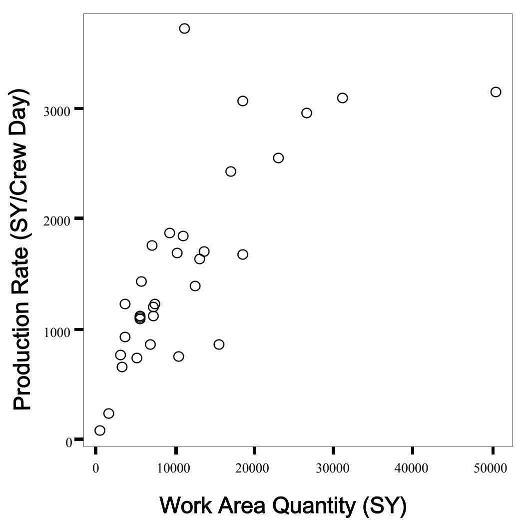


Figure 6.12 Scatter Plot for Lime-Treated Sub-grade: Production Rate (SY/Crew Day) vs. Work Area Quantity (SY)

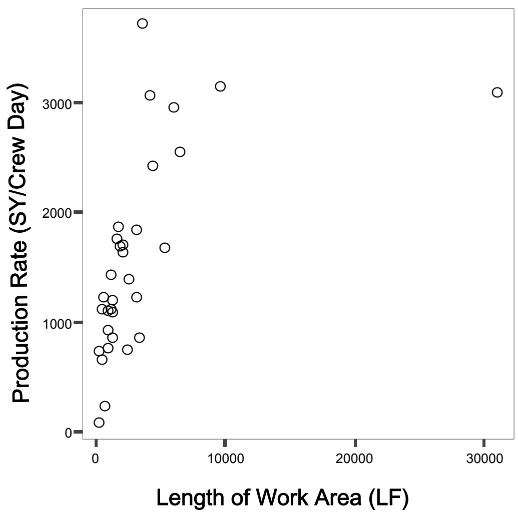


Figure 6.13 Scatter Plot for Lime-Treated Sub-grade: Production Rate (SY/Crew Day) vs. Length of Work Area (LF)

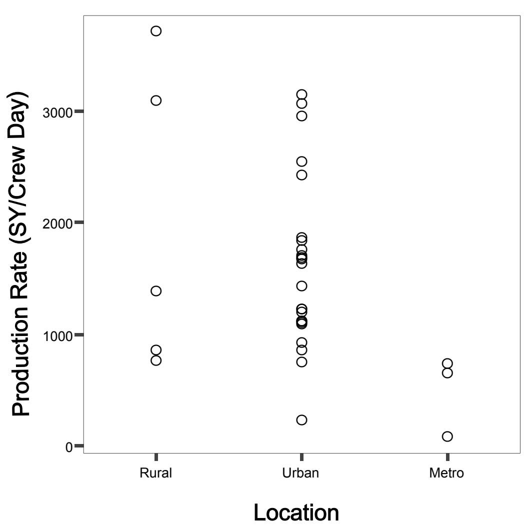


Figure 6.14 Scatter Plot for Lime-Treated Sub-grade: Production Rate (SY/Crew Day) vs. Location

6.2.3.1 Lime-Treated Sub-grade: Observed Production Rates and Work Area Quantity

The logarithmic model was found to be the most efficient model for the relationship between observed Production Rates and Work Area Quantity for Lime-treated sub-grade among the three selected models. Prior to modeling, the box plots of the dependent variable and the independent variable, shown in Figure 6.15 and Figure 6.16, were employed for outlier analysis. The 3rd and 12th data points were found to be outliers and were removed before conducting further regression analysis. The fitted logarithmic model is shown in Figure 6.10.

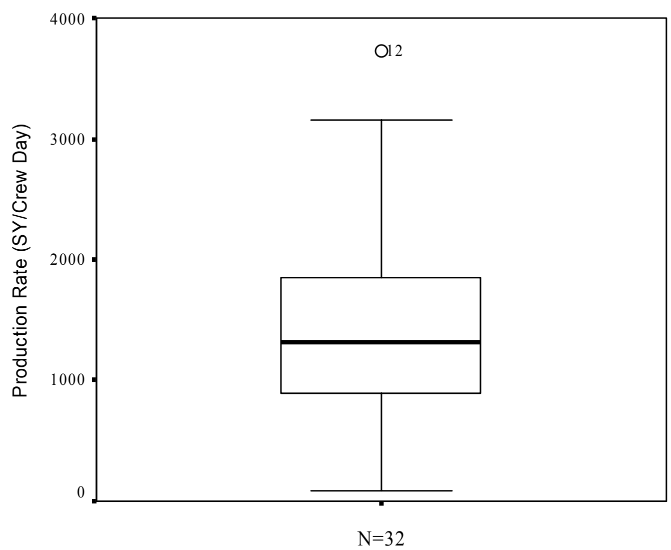


Figure 6.15 Lime-Treated Sub-grade: Box Plot of Observed Production Rates (SY/Crew Day)

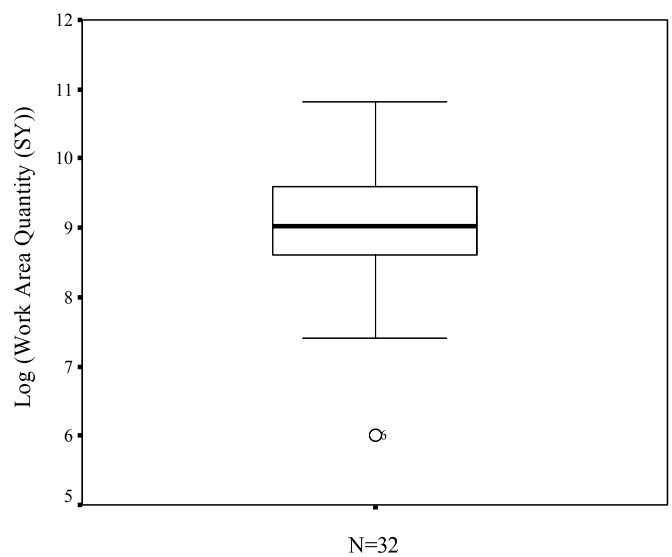


Figure 6.16 Lime-Treated Sub-grade: Box Plot of Log Transformation of Work Area Quantity (SY)

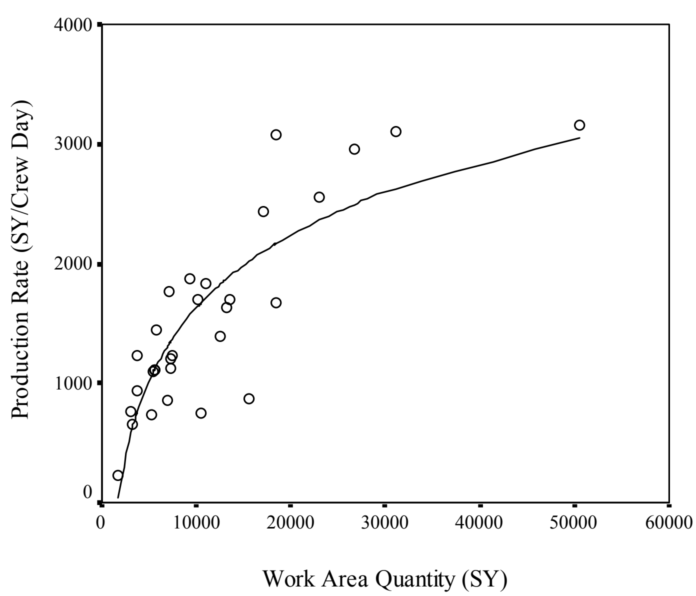


Figure 6.17 Scatter Plot and Logarithmic Model for Lime-Treated Sub-grade: Observed Production Rates (SY/Crew Day) vs. Work Area Quantity (SY)

This model, shown as Equation 6.5, was statistically significant at the 95% confidence interval. Table 6.9 displays the results of a regression analysis using the logarithmic model. The R^2 and adjusted R^2 are 0.714 and 0.704 respectively. The coefficients of this model were statistically different from zero at the 95% confidence.

Production Rate = -6457 + 878 × Log (Work Area Quantity) (Equation 6.5)

The violations of assumptions of the regression analysis were further tested for the fitted logarithmic model. The plots used to check for violations are displayed in Appendix N-1. No violation of the assumptions was found. Therefore, this model is statistically significant, meaning that Work Area Quantity affects the Production Rate of Lime-treated sub-grade construction.

Table 6.9 Logarithmic Model for Lime-Treated Sub-grade: Observed Production Rates (SY/Crew Day) by Work Area Quantity (SY)

R2		0.714
Adjusted R2		0.704
Standard Error		432
	F	P value
Regression Model	70.0	0.0000
Variable	B	P value
Work Area Quantity	-6457	0.0000
(Constant)	878	0.0010

This model is only applicable to Work Area quantities within the range of 1,632 SY to 26,645 SY, because this model was developed on this range. Therefore, the predicted Production Rates of this logarithmic model can range from 38 SY/Crew Day to 2,490 SY/Crew Day. The effect of Work Area Quantity on the Production Rate of Lime-treated sub-grade Operations can be computed by differentiation, shown in the Equation 6.6, of the fitted model. As an example, when two Work Areas have a Work Area Quantity close to 10,000 SY but have a difference of 1,000 CY in quantity, they may exhibit a difference of 88 SY/Crew Day in average Production Rate.

$$\frac{\mathbf{d(Production\ \ Rate)}}{\mathbf{d(Work\ \ Area\ \ Quantity)}} = \frac{\mathbf{878}}{\mathbf{Work\ \ Area\ \ Quantity}} \quad \text{(Equation 6.6)}$$

6.2.3.2 Lime-Treated Sub-grade: Observed Production Rates and Length of Work Area

The logarithmic model was found to be the most efficient model for the Length of Work Area for Lime-treated sub-grade. Prior to using the logarithmic model, box plots of the observed Production Rate and the logarithmic transformation of the Length of Work Area, as shown in Figure 6.15 and Figure 6.18, were employed for outlier analysis. The 11th and 12th data point were found to be outliers. These outliers were removed before conducting further regression analysis. The fitted logarithmic model, which was used to explore the relationships between the observed Production Rates and the Length of Work Area for Lime-treated sub-grade construction, is shown in Figure 6.19.

This model, shown as Equation 6.7, was statistically significant at the 95% confidence interval. Table 6.10 displays the results of a regression analysis using the logarithmic model. The R^2 and adjusted R^2 are respectively 0.631 and 0.617. The coefficients of this model were statistically different from zero at the 95% confidence interval since the P-values of the testing coefficients for Work Area Quantity and constant were less than 0.05.

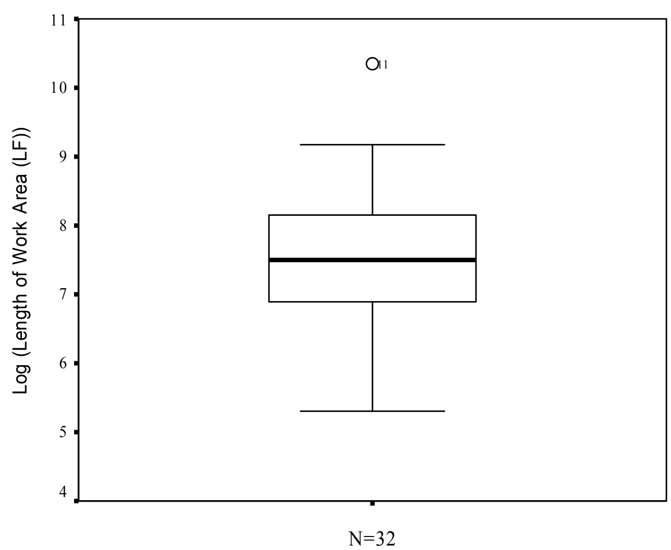


Figure 6.18 Lime-Treated Sub-grade: Box Plot of Log Transformation of Length of Work Area (LF)

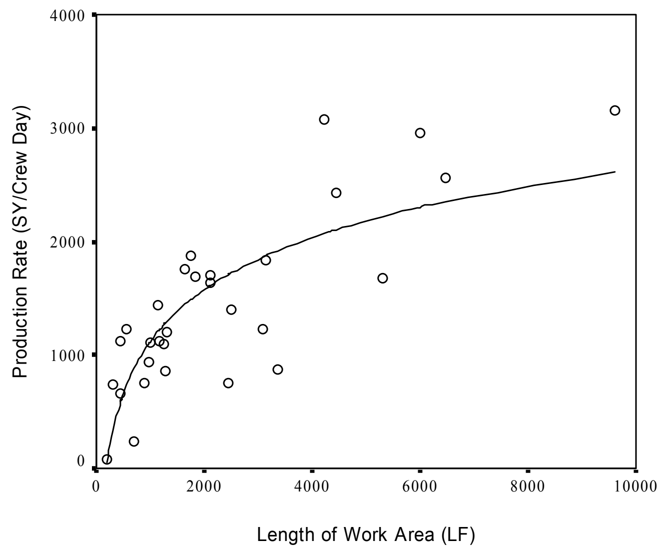


Figure 6.19 Scatter Plot and Logarithmic Model for Lime-Treated Sub-grade: Observed Production Rates (SY/Crew Day) vs. Length of Work Area Quantity (LF)

Production Rate = -3446 + 661 × Log (Length of Work Area) (Equation 6.7)

Table 6.10 Logarithmic Model for Lime-Treated Sub-grade: Production Rates (SY/Crew Day) by Length of Work Area (LF)

R2		0.631
Adjusted R2		0.617
Standard Error		483
	F	P value
Regression Model	47.79	0.0000
Variable	B	P value
Length of Work Area	661	0.0000
(Constant)	-3446	0.0000

The plots used to check for violations of the assumptions are displayed in Appendix N-2. No violation of the assumptions was found, as the plots indicate. Therefore, this model is statistically significant and the effects of Length of Work Area on the Production Rate of Lime-treated sub-grade are identified.

This model is only applicable to Length of Work Area within the range of 1,632 LF to 50,490 LF, since this model was developed based on observed data in this range. Therefore, the estimated Production Rates of this model can range from 1,444 SY/Crew Day to 3,712 SY/Crew Day. The effects of the Length of Work Area on the Production Rates of Lime-treated sub-grade Operations can be computed by differentiation of the fitted model, as shown in the Equation 6.8. Therefore, when two Work Areas have a length close to 10,000 LF but have a difference of about 1,000 LF in length, they experience a difference of about 66 CY/Crew Day in average Production Rate.

$$\frac{\mathbf{d(Production\ Rate)}}{\mathbf{d(Length\ of\ \ Work\ \ Area)}} = \frac{\mathbf{661}}{\mathbf{Length\ of\ \ Work\ \ Area}} \qquad \text{(Equation 6.8)}$$

6.2.3.3 Lime-Treated Sub-grade: Observed Production Rates and Project location

The number of data points collected for Rural, Urban and Metro areas were respectively 5, 24 and 3. The sample size for Metro was too small for comparison. Therefore, ANOVA was used to test the difference in mean Production Rates between Rural and Urban areas. Table 6.11 presents the results of the group variances test and t-test for the two groups. A P-value of 0.018 in the group variances test indicated that the two groups did not have equal variances at a 95% confidence interval. Based on the unequal variances between the two groups, the P-value of the t-test was 0.599 which was not less than 0.05. Therefore, the Rural average Production Rate was not significantly different from Urban at the 95% confidence interval.

Table 6.11 Results of Group Variances Test and t-test for Lime-Treated Sub-grade: Project Location (Rural and Urban)

Homogeneity of Group Variances Test	
	P value
Test Equality of Group Variances	0.018

Independent-Samples T Test	
	P value
Test Equality of Means between Groups	0.599

6.2.4 Aggregate Base Course

Two types of aggregate Operations were observed for this study: Flexible base and Cement-treated base (CTB) Operations. Figure 6.20 shows their observed

Production Rates. Due to the different requirements on processing operations of these two types of Base course construction, the driver analyses were performed separately.

The scatter plots, shown in Appendix O and Appendix P for Cement-treated base and Flexible base respectively, were used to examine the relationship between eleven Candidate Drivers and observed Production Rates. Relationships between observed Production Rates and Work Area Quantity, as well as Length of Work Area were analyzed for both Cement-treated base and Flexible base Operations. These are shown in Figure 6.21, Figure 6.22, Figure 6.23 and Figure 6.24. Other Candidate Drivers were excluded from further driver analyses. Two sub-hypotheses, listed as follows and applicable to both types of Aggregate base Operations, were further tested.

Sub-hypothesis 1: Due to their repetitive nature, CTB and Flexible base may become more efficient with greater quantities. In addition, productive hours in a working day may be higher for the Work Area with greater quantity.

Sub-hypothesis 2: For Cement-treated base and Flexible base, the longer the length of a Work Area the more the number of repetitions there will be. When repetitions increase, the work will be more efficient due to learning effects.

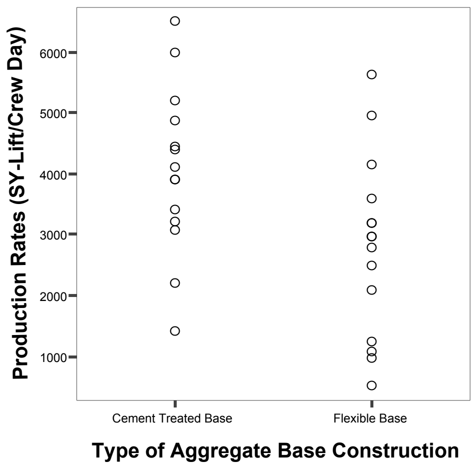


Figure 6.20 Aggregate Base: Scatter Plot of Observed Production Rates (Lift-SY/Crew Day) vs. Types of Aggregate Base Operations

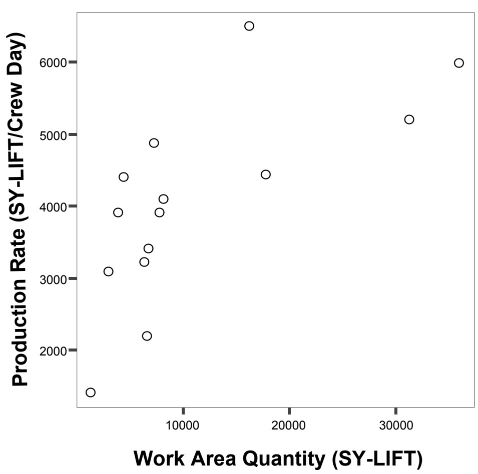


Figure 6.21 Cement-Treated Base: Scatter Plot of Observed Production Rates (Lift-SY/Crew Day) vs. Work Area Quantity (Lift-SY)

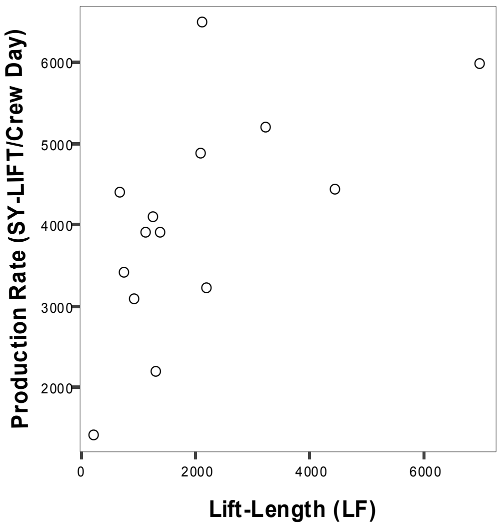


Figure 6.22 Cement-Treated Base: Scatter Plot of Observed Production Rates (Lift-SY/Crew Day) vs. Lift-Length of Work Area (LF)

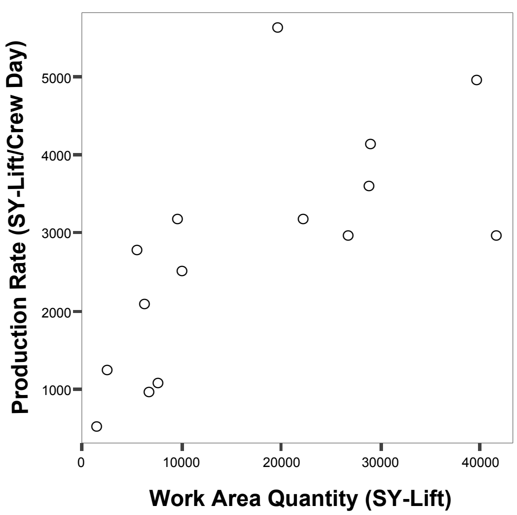


Figure 6.23 Flexible Base: Scatter Plot of Observed Production Rates (Lift-SY/Crew Day) vs. Work Area Quantity (Lift-SY)

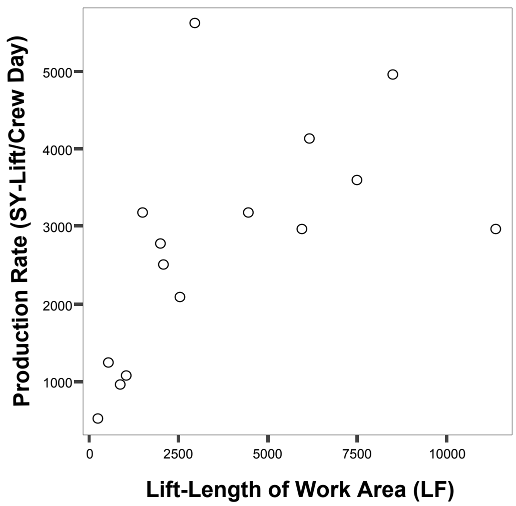


Figure 6.24 Flexible Base: Scatter Plot of Observed Production Rates (Lift-SY/Crew Day) vs. Lift-Length of Work Area (LF)

6.2.4.1 Cement-Treated Base: Observed Production Rates and Work Area Quantity

The logarithmic model was found to be the most efficient model for the relationship between observed Production Rates and Work Area Quantity for Cement-treated base, among the three selected models. The box plots of the dependent variable and the independent variable, shown in Figure 6.25 and Figure 6.26, were employed for outlier analysis. No outlier was observed from these two plots. The fitted logarithmic model is shown in Figure 6.27.

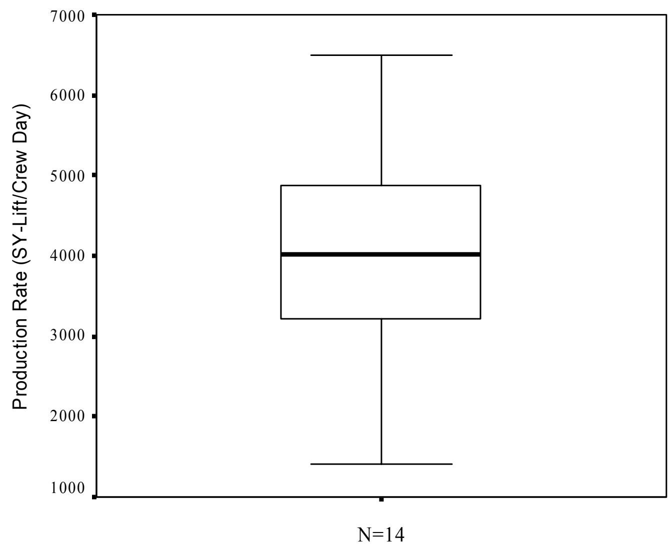


Figure 6.25 Cement-Treated Base: Box Plot of Observed Production Rates (Lift-SY/Crew Day)

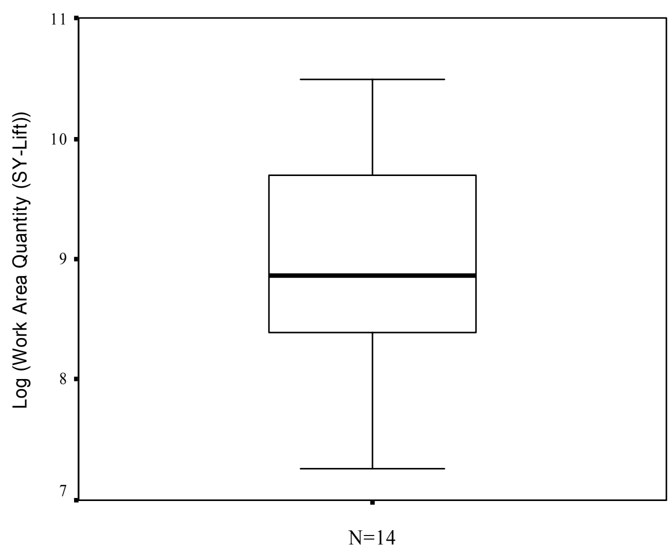


Figure 6.26 Cement-Treated Base: Box Plot of Log Transformation of Work Area Quantity (Lift-SY)

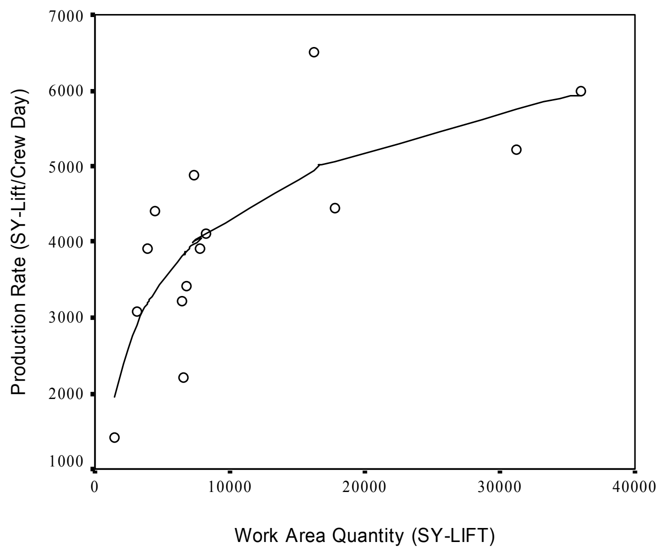


Figure 6.27 Scatter Plot and Linear Model for Cement-Treated Base: Production Rates (Lift-SY/Crew Day) vs. Work Area Quantity (Lift-SY)

This model, shown as Equation 6.9, was statistically significant at the 95% confidence interval. Table 6.12 displays the results of a regression analysis using the logarithmic model. The R^2 and adjusted R^2 are 0.627 and 0.596 respectively. The coefficients of this model were found to be statistically different from zero at the 95% confidence interval.

Production Rate = -6991 + 1231 × Log (Work Area Quantity) (Equation 6.9)

The violations of the assumptions of the regression analysis were further tested for the fitted logarithmic model and the plots used to check for them are displayed in Appendix Q-1. None were found. Therefore, this model is statistically significant, meaning that Work Area Quantity positively affects Production Rates in Cement-treated base construction, according to the fitted model.

Table 6.12 Linear Model for Cement-Treated Base: Production Rates (Lift-SY/Crew Day) by Work Area Quantity (Lift-SY)

R2		0.627
Adjusted R2		0.596
Standard Error		873.4
	F	P value
Regression Model	20.15	0.0007
Variable	B	P value
Work Area Quantity	1231	0.0007
(Constant)	-6991	0.0152

This model is only applicable for Work Area quantities between 1,416 Lift-SY and 35,956 Lift-SY. Therefore, the estimated Production Rates of this fitted logarithmic model can range from 1,941 Lift-SY/Crew Day to 5,922 SY/Crew Day. The effects of the Work Area Quantity on the Production Rates of Cement-treated base Operations can be computed from differentiation of the fitted logarithmic model, shown in the Equation 6.10. Therefore, when two Work Areas have a quantity to place close to 10,000 Lift-SY, yet are different by 1,000 Lift-SY in Length of Work Area, they will experience a difference of about 123 Lift-SY/Crew Day in average Production Rate.

$$\frac{\mathbf{d(Production\ \ Rate)}}{\mathbf{d(Work\ \ Area\ \ Quantity)}} = \frac{\mathbf{1231}}{\mathbf{Work\ \ Area\ \ Quantity}} \quad \text{(Equation 6.10)}$$

6.2.4.2 Cement-Treated Base: Observed Production Rates and Lift-length of Work Area

The linear model was found to be the most efficient model for the relationship between observed Production Rates and Lift-length of Work Area for Cement-treated base. Prior to using the linear model, the box plots of the dependent variable (i.e. the observed Production Rate) and the independent variable (i.e. the Lift-length of Work Area), as shown in Figure 6.25 and Figure 6.28, were employed for outlier analysis. The 12th and 14th data points were found to be outliers. These two outliers were removed before conducting further regression analysis. The fitted linear model is shown in Figure 6.29.

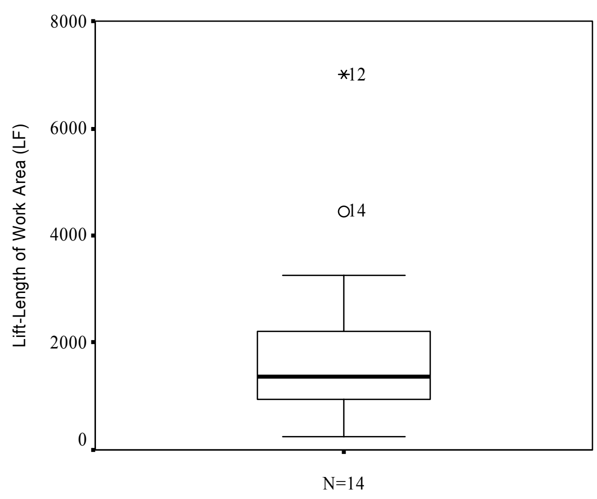


Figure 6.28 Cement-Treated Base: Box Plot of Lift-Length of Work Area (LF)

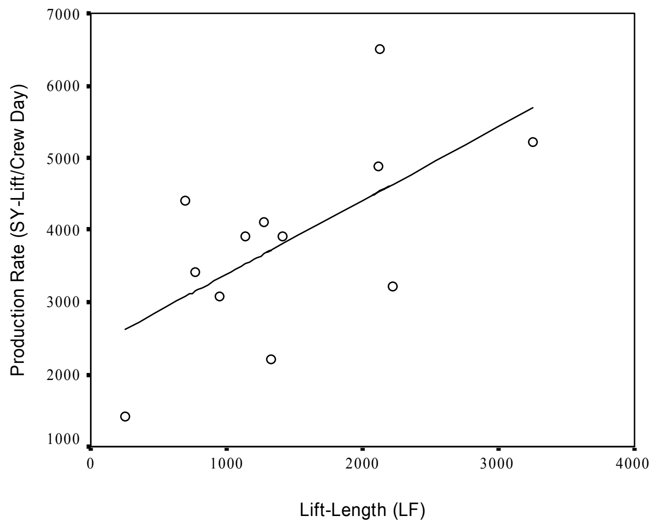


Figure 6.29 Scatter Plot and Linear Model for Cement-Treated Base: Observed Production Rates (Lift-SY/Crew Day) vs. Lift-Length of Work Area (LF)

Table 6.13 displays the results of a regression analysis to model the relationship between observed Production Rates and Lift-length of Work Area for Cement-treated base construction. This model, shown in Equation 6.11, was statistically significant at the 95% confidence interval. The R^2 and adjusted R^2 are 0.393 and 0.332 respectively. The coefficients of this fitted model were statistically different from zero at the 95% confidence interval since the P-values of testing coefficients for Work Area Quantity and constant were less than 0.05.

Production Rate = 2366 +1.02 × (Lift-Length of Work Area) (Equation 6.11)

Table 6.13 Linear Model for Cement-Treated Base: Production Rates (Lift-SY/Crew Day) by Lift-Length of Work Area (LF)

R2		0.393
Adjusted R2		0.332
Standard Error		1106
	F	P value
Regression Model	6.47	0.0291
Variable	B	P value
Lift-Length of Work Area	1.02	0.0291
(Constant)	2366	0.0053

A check for violations of the assumptions of the regression analysis was performed but none were found, as presented in Appendix Q-2. Therefore, this model is statistically significant.

This model is only applicable to Work Area quantities within the range of 250 LF to 3,250 LF. Therefore, the estimated Production Rates of the fitted linear model can range from 2,621 Lift-SY/Crew Day to 5,681 Lift-SY/Crew Day. The effects of Lift-length of Work Area on the Production Rate of Cement-treated base Operations can be computed from differentiation of the fitted model, as shown in Equation 6.12. Therefore, when two Work Areas are 100 LF different in Lift-length, they may experience a Production Rate difference of about 102 Lift-SY/Crew Day.

$$\frac{\mathbf{d(Production\quad Rate)}}{\mathbf{d(Lift-Length\quad of\quad Work\quad Area)}} = \mathbf{1.02} \qquad \text{(Equation 6.12)}$$

6.2.4.3 Flexible Base: Observed Production Rates and Work Area Quantity

The logarithmic model was found to be the best model for Flexible base. Prior to using the logarithmic model, an outlier analysis was performed but none were found. Figure 6.30 and Figure 6.31 were employed for outlier analysis. The fitted logarithmic model, which was used to identify the relationship between observed Production Rates and Work Area Quantity for Flexible base construction, is shown in Figure 6.32.

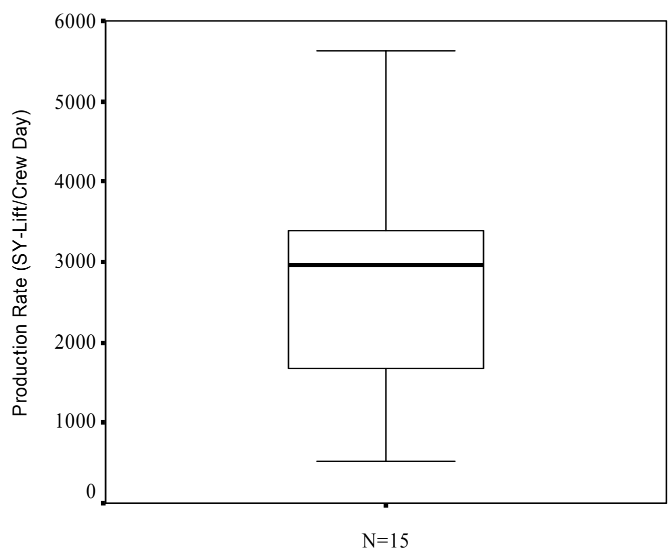


Figure 6.30 Flexible Base: Box Plot of Observed Production Rates (Lift-SY/Crew Day)

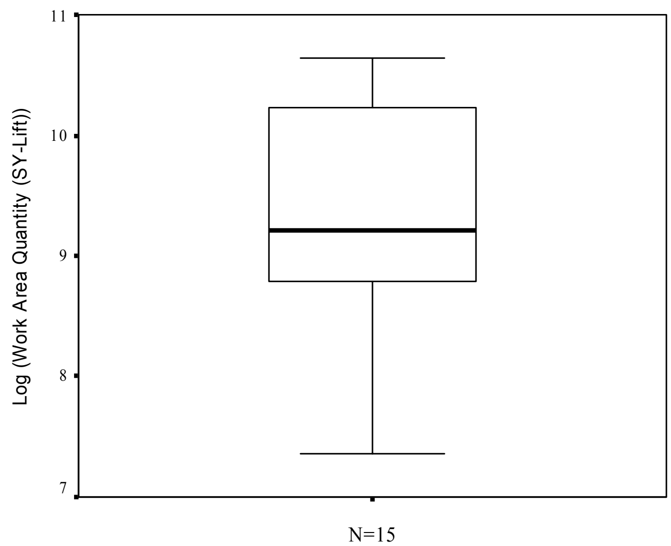


Figure 6.31 Flexible Base: Box Plot of Logarithmic Transformation of Work Area Quantity (Lift-SY)

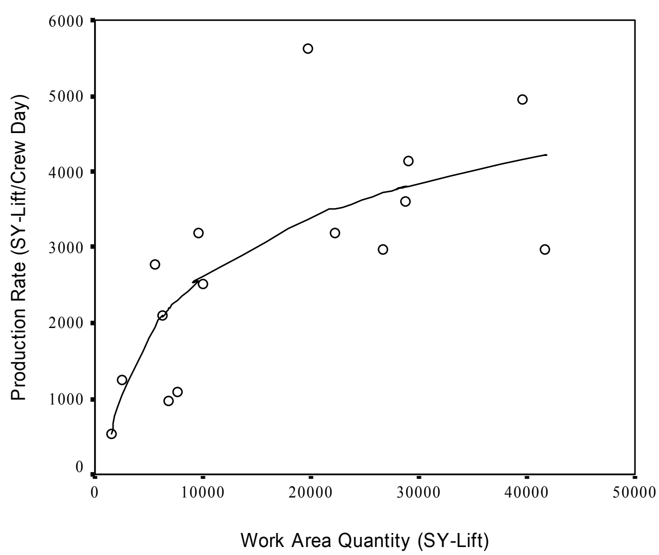


Figure 6.32 Scatter Plot and Linear Model for Flexible Base: Observed Production Rates (Lift-SY/Crew Day) vs. Work Area Quantity (Lift-SY)

Table 6.14 displays the results of a regression analysis used for the relationship between observed Production Rate and Work Area Quantity for Flexible base construction. This model, shown as Equation 6.13, is statistically significant at the 95% confidence interval. The R^2 and adjusted R^2 are 0.594 and 0.562 respectively.

Production Rate = -7761 + 1126 × Log (Work Area Quantity) (Equation 6.13)

Violations of the assumptions of regression analysis were further tested for the fitted logarithmic model and associated plots are displayed in Appendix R-1. No violation of the assumptions was found, as the plots indicate. Therefore, this model is statistically significant and the relationship between Work Area Quantity and Production Rate is identified, according to the fitted model.

Table 6.14 Logarithmic Model for Flexible Base: Production Rates (Lift-SY/Crew Day) by Work Area Quantity (Lift-SY)

R2		0.594
Adjusted R2		0.562
Standard Error		966
	F	P value
Regression Model	19	0.0008
Variable	B	P value
Work Area Quantity	1126	0.0008
(Constant)	-7761	0.0071

This model is only applicable within the range from 1,579 Lift-SY to 41,607 Lift-SY. Therefore, the estimated Production Rates of the fitted logarithmic model can range from 531 Lift-SY/Crew Day to 4,215 SY/Crew Day. The effects of Work Area Quantity on Production Rate for Flexible base Operations can be computed from differentiation of the fitted model, as shown in the Equation 6.14. Therefore, when two Work Areas have a quantity of Flexible base close to 10,000 Lift-SY but differ by 1,000 Lift-SY, they may have a difference of about 112 Lift-SY/Crew Day in average Production Rate.

$$\frac{\mathbf{d(Production\ \ Rate)}}{\mathbf{d(Work\ \ Area\ \ Quantity)}} = \frac{\mathbf{1126}}{\mathbf{Work\ \ Area\ \ Quantity}} \qquad \text{(Equation 6.14)}$$

6.2.4.4 Flexible Base: Observed Production Rates and Lift-length of Work Area

The logarithmic model was found to be the most efficient model for the relationship between observed Production Rates and Lift-length of Work Area for Flexible base. Prior to using the logarithmic model, box plots of the dependent and independent variables, shown in Figure 6.30 and Figure 6.33, were employed for outlier analysis. No outlier was observed from these two plots. The fitted logarithmic model is shown in Figure 6.34.

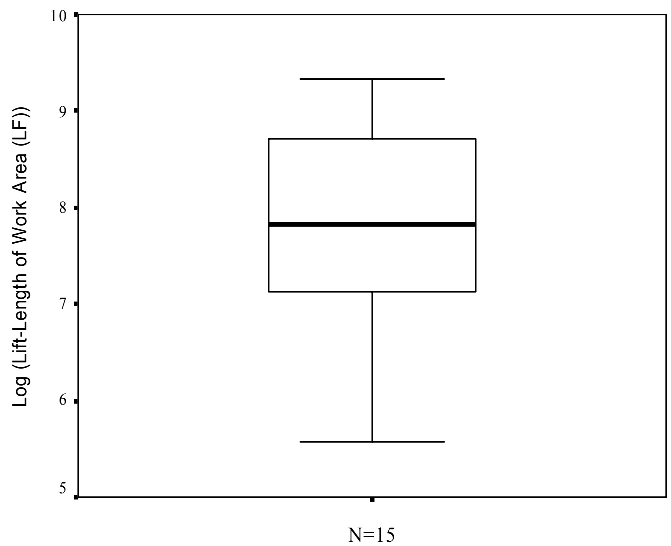


Figure 6.33 Flexible Base: Box Plot of Logarithmic Transformation of Work Area Quantity (Lift-SY)

This model, shown as Equation 6.15, was statistically significant at the 95% confidence interval. Table 6.15 displays the results of the regression analysis using the logarithmic model.

Production Rate = -4990 + 997 × Log (Lift-Length of Work Area) (Equation 6.15)

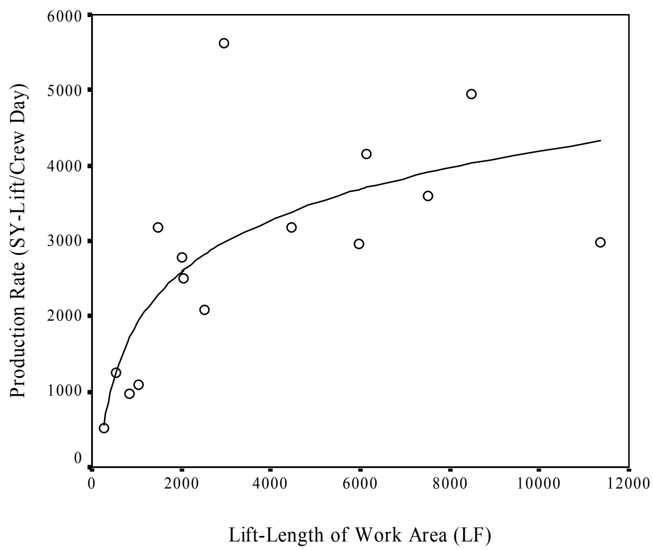


Figure 6.34 Scatter Plot and Logarithmic Model for Flexible Base: Observed Production Rates (Lift-SY/Crew Day) vs. Lift-Length of Work Area (LF)

Table 6.15 Logarithmic Model for Flexible Base: Production Rates (Lift-SY/Crew Day) by Lift-Length of Work Area (LF)

R2		0.557
Adjusted R2		0.523
Standard Error		1009
	F	P value
Regression Model	16.33	0.0014
Variable	B	P value
Length of Work Area	997	0.0014
(Constant)	-4990	0.0233

Violations of the assumptions of regression analysis were further tested for the fitted logarithmic model. The plots are displayed in Appendix R-2. No violation was found. Therefore, the fitted model is statistically significant.

This model is only applicable to Lift-length of Work Area within the range of 263 LF to 11,371 LF because this model was developed based on the observed data in this range. Therefore, the estimated Production Rates of the fitted logarithmic model can range from 565 Lift-SY/Crew Day to 4,321 Lift-SY/Crew Day. The effects of Lift-length of Work Area on Production Rate of Flexible base can be computed, as shown in the Equation 6.16. Therefore, when two Work Areas have a Lift-length of Work Area close to 10,000 Lift-SY yet differ by 1,000 Lift-SY, they may differ in Production Rate by about 100 Lift-SY/Crew Day.

$$\frac{\mathbf{d(Production\ Rate)}}{\mathbf{d(Lift-Length\ of\ \ Work\ \ Area)}} = \frac{\mathbf{997}}{\mathbf{Lift-Length\ of\ \ Work\ \ Area}}$$

(Equation 6.16)

6.3 CORRELATIONS TESTING OF DRIVERS

The next step in this study involved testing of the identified drivers for correlations. A Pearson correlation of 0 indicates that two variables are totally independent, and the interaction effects of two variables on Production Rates can be computed as the sum of the effects of each variable. In contrast, a Pearson correlation value further away from 0 indicates increasing correlation between the two variables. The combined effects of multiple variables should be obtained from further analysis, such as multiple regression analysis. If two drivers have high correlations, multicollinearity will limit the investigation of effects from a multiple regression model (Wonnacott and Wonnacott 1987).

Table 6.16 shows the correlation table of two drivers for Embankment construction. A Pearson correlation of -0.247 implies that the two drivers are not highly correlated. Therefore, the effects of the two drivers should be considered together to increase accuracy of the Production Rate model.

Table 6.16 Correlations Test for Work Area Quantity and Work Zone Congestion of Embankment Construction

	Work Zone Congestion	
Logarithmic Transformation of Work Area Quantity	-0.247	Pearson Correlations
	0.173	Sig. (2-tailed)

For Lime-treated sub-grade construction, the correlations between drivers are shown in Table 6.17. Not surprising, high correlations between Work Area Quantity and Length of Work Area were observed. Therefore, the effects of Work Area Quantity and Length of Work Area should not be considered together in one model.

Table 6.17 Correlations Test for Work Area Quantity and Length of Work Area of Lime-Treated Sub-grade Construction

	Logarithmic Transformation of Length of Work Area	
Logarithmic Transformation of Work Area Quantity	0.875**	Pearson Correlations
	0.000	Sig. (2-tailed)

**. Correlation is significant at the 0.01 level (2 tailed)

Correlations tests on Work Area Quantity and Lift-length of Work Area for Cement-treated base and Flexible base are presented in Table 6.18 and Table 6.19. Not surprising, both indicated high correlations between Work Area Quantity and Lift-length of Work Area. Therefore, they should not be considered together in one model.

Table 6.18 Correlations Test for Work Area Quantity and Lift-Length of Work Area of Cement-Treated Base Construction

	Lift-Length of Work Area	
Logarithmic Transformation of Work Area Quantity	0.854**	Pearson Correlations
	0.000	Sig. (2-tailed)

**. Correlation is significant at the 0.01 level (2 tailed)

Table 6.19 Correlations Test for Work Area Quantity and Lift-Length of Work Area of Flexible Base Construction

	Logarithmic Transformation of Lift-Length of Work Area	
Logarithmic Transformation of Work Area Quantity	0.954**	Pearson Correlations
	0.000	Sig. (2-tailed)

**. Correlation is significant at the 0.01 level (2 tailed)

6.4 EFFECTS OF MULTIPLE DRIVERS ON PRODUCTION RATES

Multiple regression analysis was used to explore the effects of multiple drivers on Production Rates for targeted Work Items. According to the required sample size for regression analysis and the assumption of independent variables, only Embankment was eligible for further multiple regression analysis.

6.4.1 Embankment: Production Rates by Logarithmic Transformation of Work Area Quantity and Work Zone Congestion

In the multiple regression analysis for Embankment, the dependent variables are estimated Production Rates and the independent variables are logarithmic transformation of Work Area Quantity and Work Zone congestion. One outlier and the data pertaining to a severely congested Work Zone were removed before conducting a multiple regression analysis. The data for Work Zone congestion were recoded as binary data (minor congested Work Zones were recoded as 0, and moderately congested Work Zones were recoded as 1).

Table 6.20 displays the results of the multiple regression analysis. The fitted model, shown as Equation 6.17, is statistically significant at the 95% confidence interval. The R^2 and adjusted R^2 are 0.4 and 0.358 respectively. The coefficients of the fitted model are statistically different from zero at the 95% confidence interval since the P-values of testing coefficients for Work Area Quantity and the constant term are less than 0.05.

Production Rate = -575 + 254 × Log (Work Area Quantity) – 313 × (Work Zone Congestion) (Equation 6.17)

Table 6.20 Multiple Regression Model for Embankment

R2		0.4
Adjusted R2		0.358
Standard Error		424
	F	P value
Regression Model	9.65	0.001
Variable	B	P value
Log (Work Area Quantity)	254	0.003
Work Zone Congestion	-313	0.055
(Constant)	-575	0.449

The test for violation of the assumption of constant variances was employed on the fitted multiple regression model. The plot used to check for the violation of the assumption is displayed in Appendix S. No violation of the assumption was found. Thus, this model is statistically significant and the effects of Work Area Quantity and Work Zone congestion on Production Rates were further quantified.

This model is only applicable for Work Area quantities within the range of 1,064 CY to 33,938 CY, and not for the Work Zones with severe congestion. Therefore, the estimated Production Rates of this model can range from 882 CY/Crew Day to 2,075 CY/Crew Day. The effects of Work Area Quantity on the Production Rates of Embankment Operations can be computed by differentiation of the fitted multiple regression model, as shown in Equation 6.18. Therefore, when two Work Areas have the quantity of Embankment close to 10,000 CY but differ by 1,000 CY in quantity, they may have a difference of about 25 CY/Crew Day in average Production Rate. The effect of minor Work Zone congestion results in a Production Rate of 313 CY/Crew Day better than moderate Work Zone congestion.

$$\frac{\mathbf{d(Production\ \ Rate)}}{\mathbf{d(Work\ \ Area\ \ Quantity)}} = \frac{\mathbf{254}}{\mathbf{Work\ \ Area\ \ Quantity}} \quad \text{(Equation 6.18)}$$

6.5 Summary of Findings on Driver Analyses

Table 6.21 summarizes the results of driver analysis. Project type was not analyzed due to insufficient data. None of the investigated Candidate Drivers at the project level was found to significantly affect Production Rates. For Candidate Drivers at the Work Zone-level, only Work Zone congestion was found to be a Production Rate driver for Embankment. For Candidate Drivers at the Work Item-level, Work Area Quantity was identified as a driver for the four targeted Earthwork-related Work Items. Length of Work Area was identified as a Production Rate driver of Lime-treated sub-grade and Aggregate base.

Table 6.21 Summary of Results of Driver Analyses

	Candidate Drivers	Excavation	Embankmant	Lime-Treated Sub-grade	Flexible Base	Cement Treated Base
Project Level	Project Type	⊕	⊕	⊕	⊕	⊕
	Project Location	○	○	○	○	○
	Traffic Flow	○	○			
	Project Complexity	○	○	○	○	○
	Accelerated Construction Provision	○	○	○	○	○
	Contractor Management Skill	○	○	○	○	○
Work Zone Level	Work Zone Accessibility	○	○			
	Work Zone Congestion	○	●	○	○	○
	Work Zone Drainage Effectiveness	○	○			
	Work Zone Clay Content			○		
	Work Zone Land Slope			○	○	○
Work Item Level	Work Area Quantity	●	●	●	●	●
	Soil Condition	○	○	○		
	Length of Work Area			●	● (Lift-Length)	●
	Type of Lime Used			○		
	Thickness			○	○ (Lift)	○
	Width of Work Area				○	○

●: Driver found to be statistically significant
○: Investigated but not statistically significant
⊕: Insufficient data for analysis

Table 6.22 lists the identified drivers that have a statistically significant relationship with Production Rates for major Earthwork construction Work Items. A multiple regression model was developed for Embankment to illustrate interaction effects of the identified drivers. For Lime-treated sub-grade and Aggregate base, multiple regression analysis is not applicable because of a high correlation between drivers.

Table 6.22 Summary of Identified Production Rate Drivers

Work Item		**Drivers**	**Type of Regression Model used for Analysis**	**Regression Analysis/T Test**	**Multiple Regression Analysis**
Excavation		Work Area Quantity	Log model	R^2= 0.692	None
Embankment		Work Area Quantity	Log model	R^2= 0.343	R^2= 0.4
		Work Zone Congestion	********	P=0.009	Adjusted R^2= 0.358
Lime Treated Sub-grade		Work Area Quantity	Log model	R^2= 0.714	*None
		Length of Work Area	Log model	R^2= 0.631	
Aggregate Base	Cement Treated Base	Work Area Quantity	Log model	R^2= 0.627	*None
		Length of Work Area	Linear Model	R^2= 0.393	
	Flexible Base	Work Area Quantity	Log model	R^2= 0.594	*None
		Length of Work Area	Log model	R^2= 0.557	

*None: Because the two drivers are highly correlated, multiple regression analysis is not applicable.
**None: The sample size was not sufficient for multiple regression analysis.

CHAPTER VII: DATA ANALYSIS AND HYPOTHESIS TESTS FOR PAVEMENT-RELATED WORK ITEMS

7.1 TEST DIFFERENCE IN MEAN PRODUCTION RATES

The mean observed Production Rates of Pavement-related Work Items were compared with average CTDS rates to test the first hypothesis which is presented as follows:

Hypothesis 1: The Production Rates of the CTDS are not realistic.

The established null hypothesis is that the mean observed Production Rates are equivalent to the average CTDS rates. In other words, the established alternative hypothesis is that the average CTDS Production Rates are different from mean observed Production Rates.

The results of the hypothesis testing are displayed in Table 7.1. Conventional form concrete pavement was excluded in this hypothesis test since its Production Rates are not available from the CTDS. It appears that the Production Rates of the CTDS are too optimistic for Hot mix asphalt pavement (HMAP) and Slip-form concrete pavement.

Table 7.1 Average CTDS Production Rates and Mean Observed Production Rates for HMAP and Slip-form Concrete Pavement

Work Item	Number of Data Points	Unit	Mean Observed Production Rate	Average CTDS Rate	Mean Difference	P-Value
Hot Mix Asphalt Pavement	32	TON/Crew Day	817	1200	-383	*0.000
Slip-form Concrete Pavement	20	SY-Lift/Crew Day	1253	3000	-1747	*0.000

* indicates that P-value is less than 0.05 and thus, the null hypothesis (Mean Observed Production Rate = Average CTDS Rate) is rejected at 95% confidence interval.

7.2 ANALYSIS OF DRIVERS OF PRODUCTION RATES

Several Candidate Drivers were selected in Section 4.1 and further investigated for their effects on Production Rates. The following is the formulation of the second hypothesis.

Hypothesis 2: The Production Rates of the targeted Work Items are driven by some productivity factors that are known at the design stage.

7.2.1 Hot Mix Asphalt Pavement

The scatter plots, shown in Appendix T, were used to examine the relationships between eleven Candidate Drivers and observed Production Rates for Hot mix asphalt pavement Operations. Relationships for Work Area Quantity and Difference in mean Production Rate for Course types were observed. The scatter plots of these two Candidate Drivers are shown in Figures 7.1 and 7.2. Other Candidate Drivers were excluded from further driver analyses. The two sub-hypotheses, listed as follows, were tested further.

Sub-hypothesis 1: Hot mix asphalt pavement Operations may experience increased productivity in larger Operations. In addition, Work Area with higher quantity may yield more effective daily working hours.

Sub-hypothesis 2: Surface courses are usually built to a higher standard of quality than Base courses, therefore Hot mix asphalt pavement Base course Operations may have higher Production Rates.

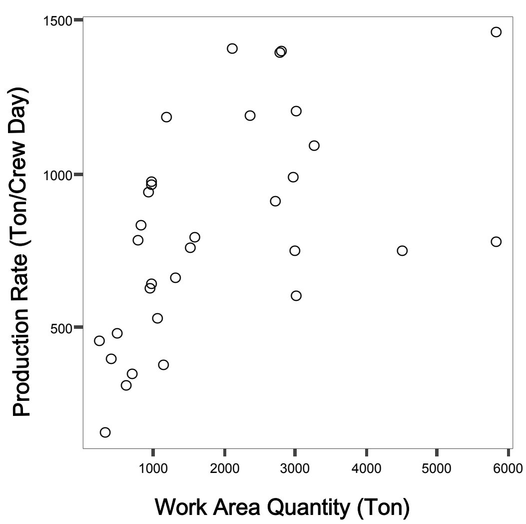


Figure 7.1 Hot Mix Asphalt Pavement: Scatter Plot of Observed Production Rates (Ton/Crew Day) vs. Work Area Quantity (Ton)

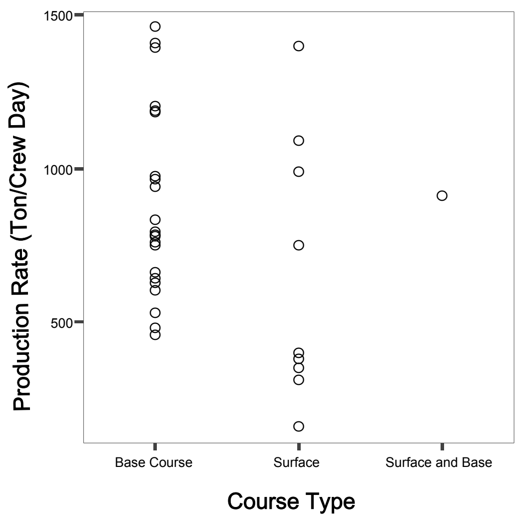


Figure 7.2 Hot Mix Asphalt Pavement: Scatter Plot of Observed Production Rates (Ton/Crew Day) vs. Course Type

7.2.1.1 Hot Mix Asphalt Pavement: Observed Production Rates and Work Area Quantity

The logarithmic model was found to be the most efficient model for the relationship between observed Production Rates and Work Area Quantity for Hot mix asphalt pavement among three selected models (linear model, logarithmic model and power model). Box plots, shown in Figure 7.3 and Figure 7.4, were employed for outlier analysis. No outlier was observed. The fitted logarithmic model is shown in Figure 7.5.

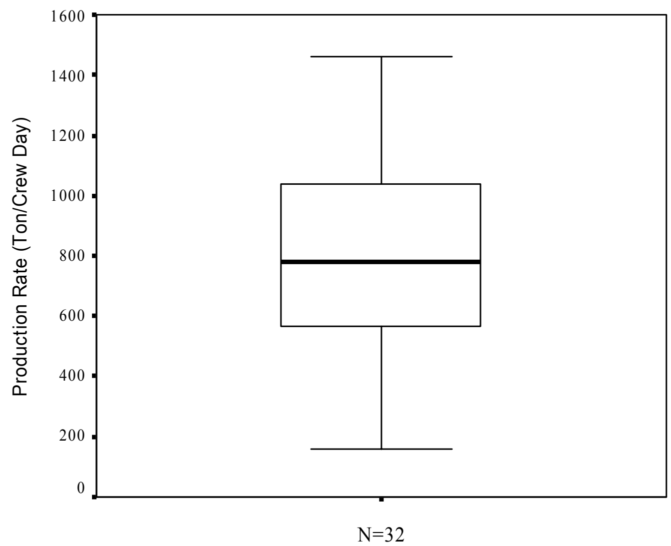


Figure 7.3 Hot Mix Asphalt Pavement: Box Plot of Observed Production Rates (Ton/Crew Day)

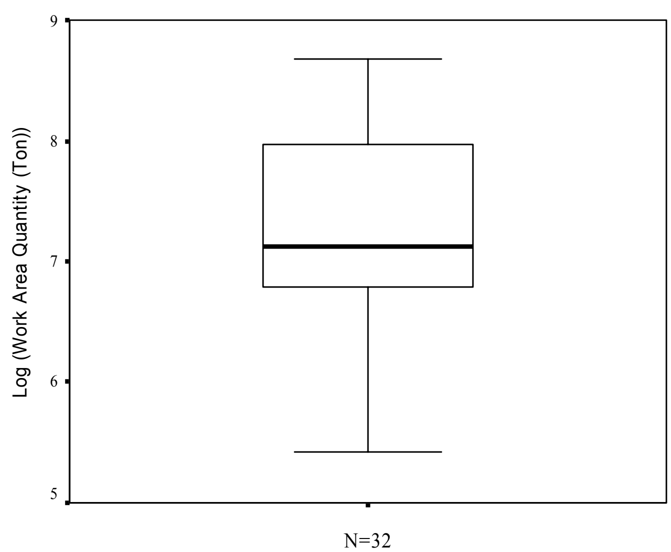


Figure 7.4 Hot Mix Asphalt Pavement: Box Plot of Logarithmic Transformation of Work Area Quantity (Ton)

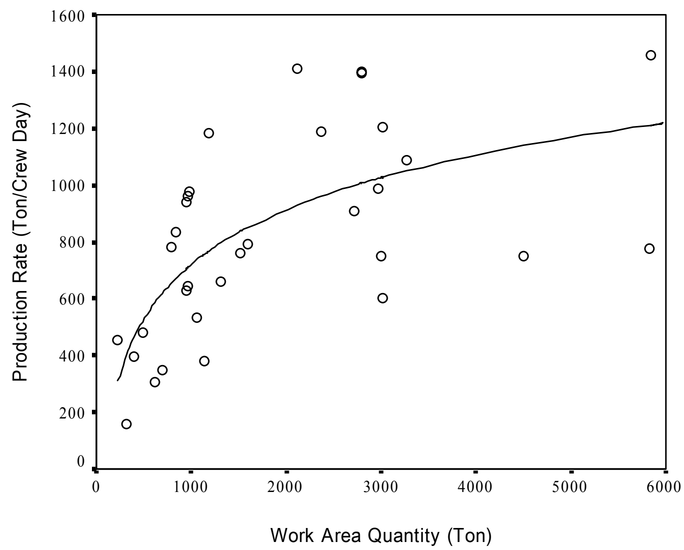


Figure 7.5 Scatter Plot and Logarithmic Model for Hot Mix Asphalt Pavement: Observed Production Rates (Ton/Crew Day) vs. Work Area Quantity (Ton)

The fitted model, shown as Equation 7.1, was found to be statistically significant at the 95% confidence interval. Table 7.2 displays the results of a regression analysis using the logarithmic model. The R^2 and adjusted R^2 are 0.432 and 0.414 respectively.

Production Rate = -1198 + 278 × Log (Work Area Quantity) (Equation 7.1)

No violation of assumptions was found, as shown in Appendix U-1. Therefore, this model is statistically significant. This model is only applicable to Work Area quantities within the range of 227 Tons to 5,840 Tons. Therefore, the estimated Production Rates of the fitted logarithmic model can range from 310 Tons/Crew Day to 1,213 Tons/Crew Day. The effects of Work Area Quantity on the Production Rates of Hot mix asphalt pavement can be computed from differentiation of the fitted model, as shown in the Equation 7.2. As an example, when two Work Areas have a quantity of Hot mix asphalt pavement close to 1,000 Tons but differ by 100 Tons in total quantity, they may experience a difference of about 28 Tons/Crew Day in average Production Rate.

Table 7.2 Logarithmic Model for Hot Mix Asphalt Pavement: Production Rates (Ton/Crew Day) by Work Area Quantity (Ton)

R2		0.432
Adjusted R2		0.414
Standard Error		268
	F	P value
Regression Model	22.86	0.0000
Variable	B	P value
Work Area Quantity	278	0.0000
(Constant)	-1198	0.0083

$$\frac{\mathbf{d(Production\ \ Rate)}}{\mathbf{d(Work\ \ Area\ \ Quantity)}} = \frac{\mathbf{278}}{\mathbf{(Work\ \ Area\ \ Quantity)}} \quad \text{(Equation 7.2)}$$

7.2.1.2 Hot Mix Asphalt Pavement: Observed Production Rates and Course type

A total of thirty-two data points were observed in this portion of the study. Twenty-two pertained to Base course construction and nine pertained to Surface course. One observation included both Surface and Base course construction. In order to investigate Production Rate difference between Base and Surface course, the data point observed with both Surface and Base course construction was removed. The t-test was employed to test the difference in mean Production Rate between Surface and Base course construction, since the two groups are independent and both groups are normally distributed (Appendix U-2). Table 7.3 presents the results of the t-test for the two groups. The homogeneity testing of variance yield a P-value of 0.103, thus, indicated that the two groups had equal variance at 90% confidence interval. Based on the assumption of equal variance between two groups, the P-value of t-test was 0.093, which was less than 0.1. Therefore, it can be concluded that the average Production Rate between Surface and Base course construction is different at the 90% confidence interval.

Table 7.3 Results of Group Variances Test and ANOVA Test for Hot Mix Asphalt Pavement: Course Type

Homogeneity of Group Variances Test	
	P value
Test Equality of Group Variances	0.103

Independent-Samples T Test	
	P value
Test Equality of Means among Groups	0.093

Table 7.4 shows that the average Production Rate of Surface course construction was 646 Tons/Crew Day and the average Production Rate of the Base course construction was 882 Tons/Crew Day. The difference of average Production Rate between the two types of course construction was 236 Tons/Crew Day.

Table 7.4 Hot Mix Asphalt Pavement: Numbers of Data Points and Mean Production Rate

	Number of Data Points	Mean Production Rate (Tons/Crew Day)
Base Course	22	882
Surface Course	9	646

7.2.2 Slip-form Concrete Pavement

The scatter plots, shown in Appendix V, were used to examine the relationship between fourteen Candidate Drivers and observed Production Rates for Slip-form concrete pavement. Relationships for Work Area Quantity and Length of Work Area were observed. The scatter plots for these two Candidate Drivers are shown in Figure 7.6 and Figure 7.7.

Sub-hypothesis 1: Slip-form concrete pavement Operations may experience increased Production Rate for larger Operations. In addition, Work Areas with higher quantity may yield more effective daily working hours.

Sub-hypothesis 2: A longer Length of Work Area may contribute to increased Production Rate.

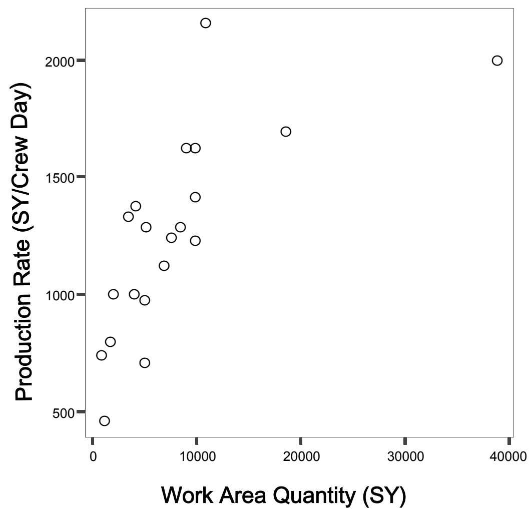


Figure 7.6 Slip-form Concrete Pavement: Scatter Plot of Observed Production Rates (SY/Crew Day) vs. Work Area Quantity (SY)

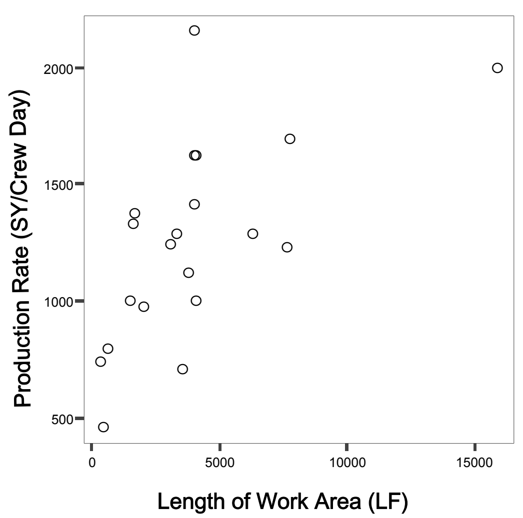


Figure 7.7 Slip-form Concrete Pavement: Scatter Plot of Observed Production Rates (SY/Crew Day) vs. Length of Work Area (LF)

7.2.2.1 Slip-form Concrete Pavement: Observed Production Rates and Work Area Quantity

The logarithmic model was found to be the most efficient model for the relationship between observed Production Rates and Work Area Quantity for Slip-form concrete pavement. Prior to using the fitted logarithmic model to model the relationships, the box plots, shown in Figures 7.8 and 7.9, were employed for outlier analysis. The 4th data points were found to be an outlier. It was removed before conducting further regression analysis. The fitted logarithmic model for Slip-form concrete pavement construction is shown in Figure 7.10.

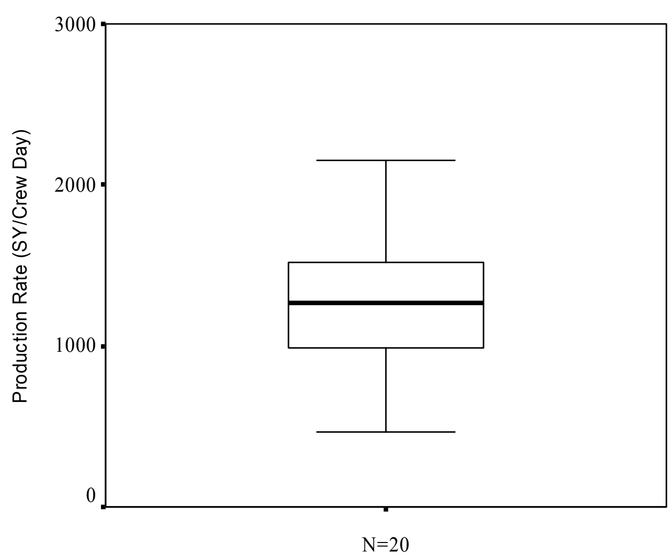


Figure 7.8 Slip-form Concrete Pavement: Box Plot of Observed Production Rates (SY/Crew Day)

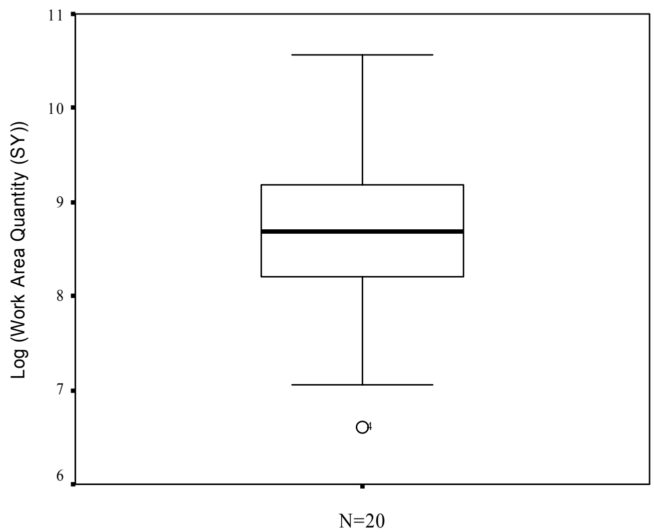


Figure 7.9 Slip-form Concrete Pavement: Box Plot of Logarithmic Transformation of Work Area Quantity (SY)

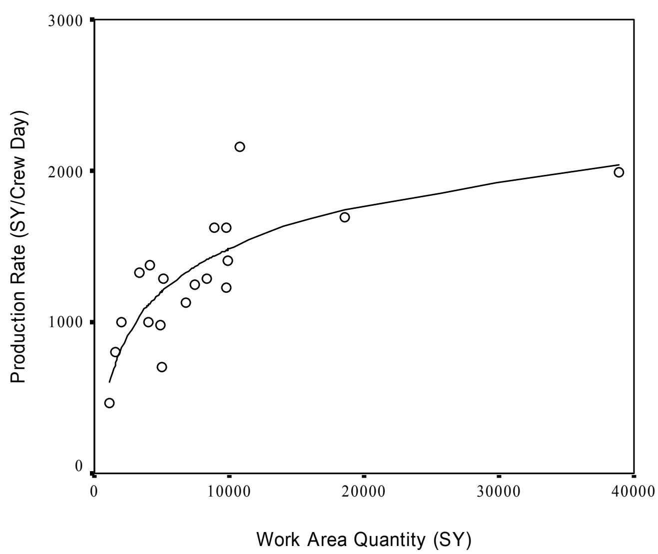


Figure 7.10 Scatter Plots and Logarithmic Model for Slip-form Concrete Pavement: Observed Production Rates (SY/Crew Day) vs. Work Area Quantity (SY)

This model, shown as Equation 7.3, is statistically significant at the 95% confidence interval. Table 7.5 displays the results of a regression analysis using the logarithmic model. The R^2 and adjusted R^2 are 0.653 and 0.632 respectively. The coefficients of this model were statistically different from zero at the 95% confidence interval since the P-values of testing coefficients for Work Area Quantity and constant term were less than 0.05.

Production Rate = -2274 + 408 × Log (Work Area Quantity) (Equation 7.3)

Table 7.5 Logarithmic Model for Slip-form Concrete Pavement: Production Rates (SY/Crew Day) by Work Area Quantity (SY)

R2		0.653
Adjusted R2		0.632
Standard Error		256
	F	P value
Regression Model	32	0.0000
Variable	B	P value
Work Area Quantity	408	0.0000
(Constant)	-2274	0.0022

The plots used to check for violations of the assumptions are displayed in Appendix W-1, and none were found. Therefore, the fitted model is statistically significant. This model is only applicable to Work Area quantities within the range of 1,156 SY to 18,592 SY. Therefore, the estimated Production Rates of the fitted logarithmic model can range from 591 SY/Crew Day to 1,752 SY/Crew Day. The effects of the Work Area Quantity on the Production Rates of Slip-form concrete pavement construction can be computed from differentiation of the fitted model, as shown in the Equation 7.4. Therefore, when two Work Areas have the quantity of Slip-form concrete pavement close to 10,000 SY and yet differ by 1,000 SY in Work Area Quantity, productivity may differ by 42 SY/Crew Day in the average daily Production Rate.

$$\frac{\textbf{d(Production Rate)}}{\textbf{d(Work Area Quantity)}} = \frac{\textbf{418}}{\textbf{(Work Area Quantity)}} \quad \text{(Equation 7.4)}$$

7.2.2.2 Slip-form Concrete Pavement: Observed Production Rates and Length of Work Area

The logarithmic model was found to be the most efficient model for the relationship between observed Production Rates and Length of Work Area for Slip-form concrete pavement construction. Prior to using the logarithmic model to model the relationship, the box plots of the dependent variable (i.e. the observed Production Rate) and the independent variable (i.e. the logarithmic transformation of Length of Work Area), shown in Figure 7.8 and Figure 7.11, were employed for outlier analysis. The 4th and 7th data points were found to be outliers. Two outliers were removed before conducting further regression analysis. The fitted logarithmic model for Slip-form concrete pavement construction is shown in Figure 7.12.

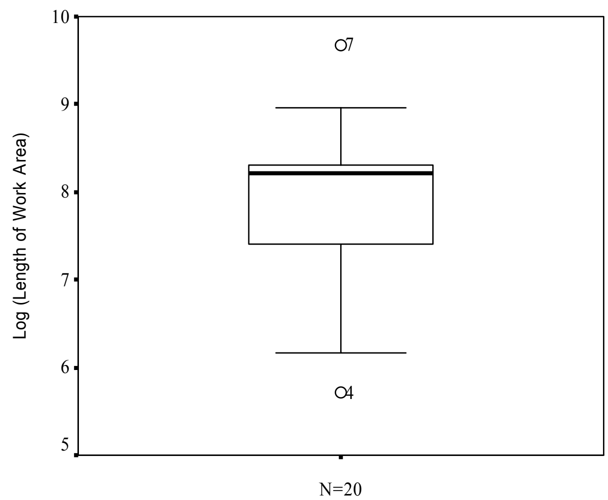


Figure 7.11 Slip-form Concrete Pavement: Box Plot of Logarithmic Transformation of Length of Work (LF)

The fitted model, shown as Equation 7.5, was statistically significant at the 95% confidence interval. Table 7.6 displays the results of a regression analysis that models the relationship of observed Production Rates and Length of Work Area for Slip-form concrete pavement construction. The R^2 and adjusted R^2 were respectively 0.356 and 0.316. The coefficient for the Length of Work Area of the fitted model was statistically different from zero at the 95% confidence interval. Although the constant term was not statistically different from zero in the fitted model at the 95% confidence interval, the fitted model can still be used to quantify the relationship between Work Area Quantity and observed Production Rates.

Production Rate = -1193 + 306 × Log (Length of Work Area) (Equation 7.5)

Violations of the assumptions of regression analysis were further tested for the fitted logarithmic model and are displayed in Appendix W-2. No violation of the assumptions was found, as the plots indicate. Therefore, the fitted model is statistically significant, meaning that Length of Work Area significantly affects Production Rates in Slip-form concrete pavement according to the fitted model.

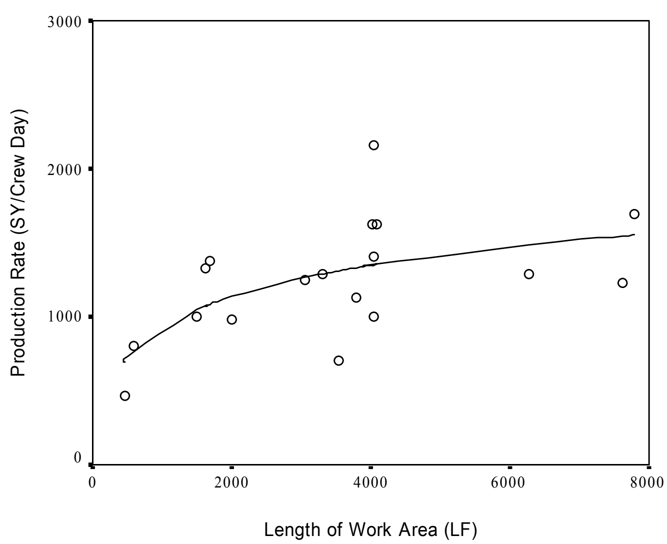


Figure 7.12 Scatter Plot and Logarithmic Model for Slip-form Concrete Pavement: Observed Production Rates (SY/Crew Day) vs. Work Area Quantity (SY)

Table 7.6 Logarithmic Model for Slip-form Concrete Pavement: Production Rates (SY/Crew Day) by Work Area Quantity (SY)

R2		0.356
Adjusted R2		0.316
Standard Error		328
	F	P value
Regression Model	8.85	0.0089
Variable	B	P value
Length of Work Area	306	0.0089
(Constant)	-1193	0.1659

This model is only applicable to Length of Work Area with the range from 473 LF to 7,783 LF. Therefore, the estimated Production Rates of the fitted logarithmic model can range from 692 SY/Crew Day to 1,549 SY/Crew Day. The effects of the Length of Work Area on the Production Rates of Slip-form concrete pavement construction can be computed from differentiation of the fitted model, as shown in the Equation 7.6. Therefore, two Work Areas with Length of Work Area close to 1,000 LF and that differ by 100 LF may show a difference of about 31 SY/Crew Day in the average Production Rate.

$$\frac{\mathbf{d(Production\ Rate)}}{\mathbf{d(Length\ of\ Work\ Area)}} = \frac{\mathbf{306}}{\mathbf{(Length\ of\ Work\ Area)}} \quad \text{(Equation 7.6)}$$

7.2.3 Analysis of Drivers of Production Rates for Conventional Form Concrete Pavement

The scatter plots shown in Appendix X were used to examine the relationship between fourteen Candidate Drivers and observed Production Rates for Conventional form concrete pavement. Relationships for Work Area Quantity were found as well as for different types of Configuration. The scatter plots of these two Candidate Drivers are shown in Figure 7.13 and Figure 7.14. Other Candidate Drivers were excluded from further analysis.

Sub-hypothesis 1: Repetition and higher quantities should contribute to an increased Production Rate for Conventional form concrete pavement. In addition, Work Areas with higher quantity may yield more effective daily working hours.

Sub-hypothesis 2: Formwork and rebar installation for Convention form concrete pavement with curves or sharp angles take longer than for the Concrete pavement with regular shapes. This may explain why Concrete pavement Operations with curve(s) or sharp angle(s) have lower Production Rates.

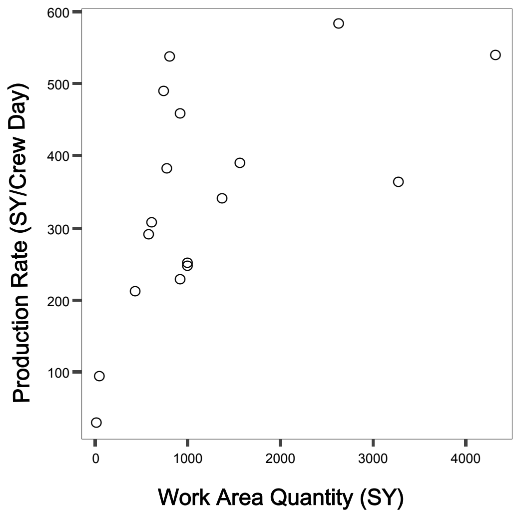


Figure 7.13 Conventional Form Concrete Pavement: Scatter Plot of Observed Production Rates (SY/Crew Day) vs. Work Area Quantity (SY)

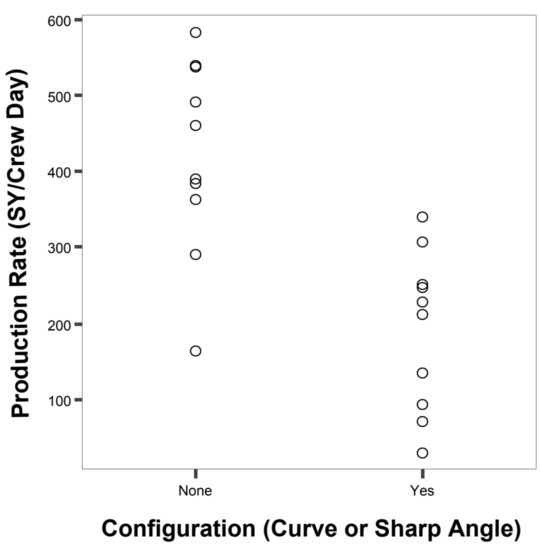


Figure 7.14 Conventional Form Concrete Pavement: Scatter Plot of Observed Production Rates (SY/Crew Day) vs. Configuration

7.2.3.1 Conventional Form Concrete Pavement: Observed Production Rates and Work Area Quantity

The logarithmic model was found to be the best model for the relationship between observed Production Rates and Work Area Quantity for Conventional form concrete pavement. Prior to using the logarithmic model, box plots shown in Figure 7.15 and Figure 7.16 were employed for outlier analysis. The 13th and 14th data points were found to be outliers. These outliers were removed before conducting the regression analysis. The fitted logarithmic model for Conventional form concrete pavement construction is shown in Figure 7.17.

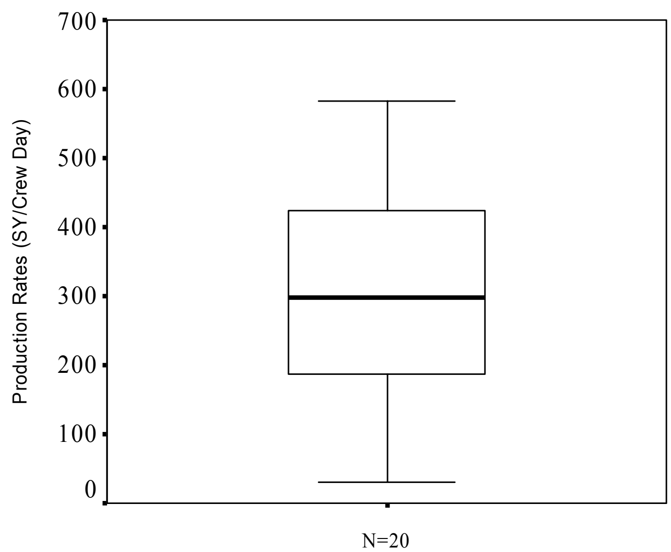


Figure 7.15 Conventional Form Concrete Pavement: Box Plot of Observed Production Rates (SY/Crew Day)

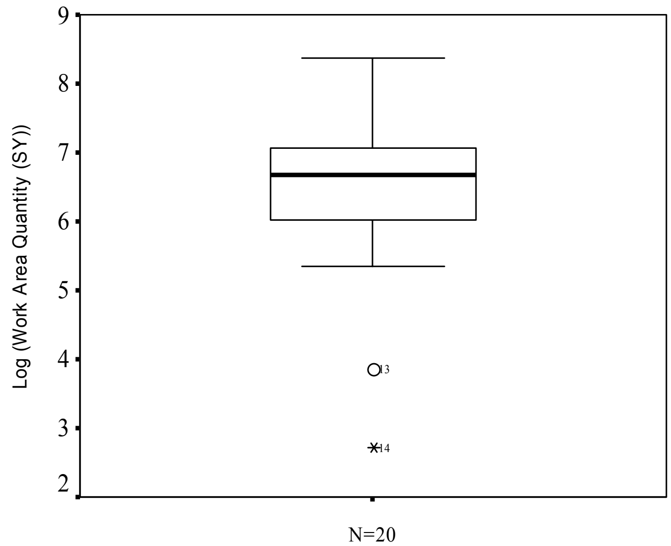


Figure 7.16 Conventional Form Concrete Pavement: Box Plot of Logarithmic Transformation of Work Area Quantity (SY)

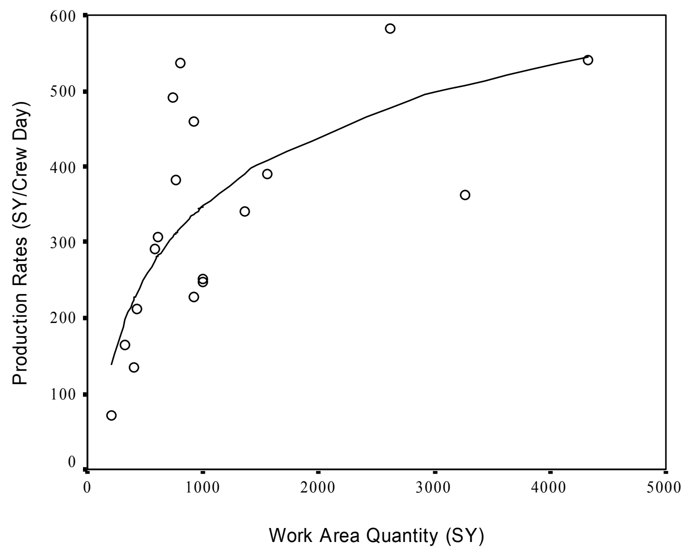


Figure 7.17 Pavement: Observed Production Rates (SY/Crew Day) vs. Logarithmic Transformation of Work Area Quantity (SY)

Table 7.7 displays the results of a regression analysis using the logarithmic model. The fitted model, shown in Equation 6.23, is statistically significant at the 95% confidence interval. The R^2 and adjusted R^2 are 0.511 and 0.481 respectively. The coefficients of the fitted model are statistically different from zero at the 95% confidence interval since the P-values of testing coefficients for Work Area Quantity and the constant term were less than 0.05.

Production Rate = -583 + 135 × Log (Work Area Quantity) (Equation 7.7)

Violations of the assumptions of regression analysis were further tested for the fitted logarithmic model, and the plots used to check for such violations are displayed in Appendix Y-1. No violation was found. Therefore, the fitted model *is* statistically significant and effects of Work Area Quantity on Production Rates were further investigated according to the fitted model.

Table 7.7 Linear Model for Conventional Form Concrete Pavement: Production Rates (SY/Crew Day) by Work Area Quantity (SY)

R2		0.511
Adjusted R2		0.481
Standard Error		107
	F	P value
Regression Model	16.7	0.0009
Variable	B	P value
Work Area Quantity	135	0.0009
(Constant)	-583	0.0200

This model is only applicable for Work Area quantities within the range of 211 SY to 4,320 SY. Therefore, the estimated Production Rates of the fitted logarithmic model can range from 140 SY/Crew Day to 547 SY/Crew Day. The effects of Work Area Quantity on Production Rates for Conventional form concrete pavement construction can be computed from differentiation of the fitted model, as shown in the Equation 7.8. Therefore, when two Work Areas have a quantity of Conventional form concrete pavement close to 1,000 SY but differ by 100 SY in quantity, they may experience about 14 SY/Crew Day difference in average Production Rate.

$$\frac{\mathbf{d(Production\ \ Rate)}}{\mathbf{d(Work\ \ Area\ \ Quantity)}} = \frac{\mathbf{135}}{\mathbf{Work\ \ Area\ \ Quantity}} \qquad \text{(Equation 7.8)}$$

7.2.3.2 Conventional Form Concrete Pavement: Observed Production Rates and Configuration

Conventional form concrete pavement observations were divided into two categories according to Configuration. The first category was for the Concrete Pavement Operation that included sharp angle(s) or curve(s). The second category was for the Concrete Pavement without any curve or sharp angle. A total of twenty data points were observed. Each category has ten observed data points. The t-test was employed to test the difference in mean Production Rate between the two categories, since the two groups are independent and both groups are normally distributed (Appendix Y-2). Table 7.8 presents the results of the group variances test and the t-test. A P-value of 0.6 of homogeneity of variances test indicated that two groups had equal variances at the 95% confidence interval. Based on the assumption of equal variances between two groups, the P-value of the t-test was 0.000 which is less than 0.05. Therefore, it can be concluded that the average Production Rates of the Conventional form concrete pavement construction are different between the two categories at the 95% confidence interval.

Table 7.9 shows that the average Production Rate for Conventional form concrete pavement construction is 420 SY/Crew Day for the Configuration without any curve or sharp angle and 192 SY/Crew Day for the Configuration with curve(s) or sharp angle(s). The difference of average Production Rate between the two categories is 228 SY/Crew Day.

Table 7.8 Results of Group Variances Test and T Test for Conventional Form Concrete Pavement: Configuration

Homogeneity of Group Variances Test	
	P value
Test Equality of Group Variances	0.6

Independent-Samples T Test	
	P value
Test Equality of Means among Groups	0.000

Table 7.9 Numbers of Data Points and Mean Production Rate for Conventional Form Concrete Pavement: Configuration

	Number of Data Points	Mean Production Rate (SY/Crew Day)
Configuration without any curve or sharp angle	10	420
Configuration with any curve or sharp angle	10	192

7. 3 CORRELATIONS TESTING OF DRIVERS

The Work Area Quantity and Course type in Hot mix asphalt pavement construction were not highly correlated according to results of the correlations test shown in Table 7.10. Therefore, the effects of the two drivers on Production Rates of Hot mix asphalt pavement should be considered simultaneously during the estimation of Production Rates.

Table 7.10 Correlations Test for Work Area Quantity and Course Type of Hot Mix Asphalt Pavement Construction

	Course Type	
Logarithmic Transformation of Work Area Quantity	0.165	Pearson Correlations
	0.367	Sig. (2-tailed)

Table 7.11 indicated a high correlation between Work Area Quantity and Length of Work Area in Slip-form concrete pavement construction. Therefore,

the effects of Work Area Quantity and Length of Work Area should not be considered at the same time during estimation of Production Rates.

Table 7.11 Correlations Test for Work Area Quantity and Length of Work Area of Slip-form Concrete Pavement Construction

	Logarithmic Transformation of Length of Work Area	
Logarithmic Transformation of Work Area Quantity	0.951**	Pearson Correlations
	0.000	Sig. (2-tailed)

**. Correlation is significant at the 0.01 level (2 tailed)

Table 7.12 shows the results of the correlations test between Work Area Quantity and Configuration for Conventional form concrete pavement. The correlation of -0.391 indicated that the Configuration is not highly correlated with Work Area Quantity. Therefore, the effects of both drivers should be considered together during estimation of the Production Rate for Conventional form concrete pavement.

Table 7.12 Correlations Test for Work Area Quantity and Configuration of Conventional Form Concrete Pavement Construction

	Configuration	
Logarithmic Transformation of Work Area Quantity	-0.391	Pearson Correlations
	0.108	Sig. (2-tailed)

7.4 EFFECTS ON MULTIPLE DRIVERS ON PRODUCTION RATES

According to the required sample size for regression analysis and the assumption of independent variables, only Hot mix asphalt pavement was eligible for further multiple regression analysis.

7.4.1 Hot Mix Asphalt Pavement: Production Rates by Logarithmic Transformation of Work Area Quantity and Course Type

In the multiple regression analysis for Hot mix asphalt pavement, the dependent variables are estimated Production Rates and the independent variables are logarithmic transformation of Work Area Quantity and Course type. The data for Course type were recoded as binary data. Data for Base course construction were recoded as 1, and Surface course construction were recoded as 0.

Table 7.13 displays the results of the multiple regression analysis. The fitted model, shown as Equation 7.9, is statistically significant at the 95% confidence interval. The R^2 and adjusted R^2 are 0.488 and 0.452 respectively.

$$\textbf{Production Rate} = -1263 + 269 \times \text{Log (Work Area Quantity)} - 181 \times \text{(Course Type)} \quad \text{(Equation 7.9)}$$

Table 7.13 Multiple Regression Model for Hot Mix Asphalt Pavement

R2		0.488
Adjusted R2		0.452
Standard Error		263
	F	P value
Regression Model	13.35	0.000
Variable	B	P value
Log (Work Area Quantity)	269	0.000
Course Type	181	0.095
(Constant)	-1263	0.006

The plots used to check for violation of assumptions are displayed in Appendix Z. No violation was found. Thus, this model was statistically significant and the effects of Work Area Quantity on Production Rate are established herein.

This model is only applicable to Work Area quantities within the range of 227 tons to 5,840 tons, since this model was developed based on the observed data that had this range. Therefore, the estimated Production Rates for Surface course construction of this model can range from 196 Tons/Crew Day to 1,070 Tons/Crew Day, and for Base course construction can range from 377 Tons/Crew Day to 1,251 Tons/Crew Day. The effects of Work Area Quantity on the Production Rate of Hot Mix Asphalt Operations can be computed by differentiation of the fitted multiple regression model, as shown in Equation 6.28. Therefore, when two Work Areas have a quantity of Hot mix asphalt pavement close to 1,000 tons but differ by 100 tons in Work Area Quantity, they may experience a difference about 27 Ton/Crew Day in average Production Rate. The effects of Course type on Production Rate of Hot mix asphalt pavement are 181 Ton/Crew Day when the two Work Areas have the same Work Area Quantity.

$$\frac{\mathbf{d(Production\ \ Rate)}}{\mathbf{d(Work\ \ Area\ \ Quantity)}} = \frac{\mathbf{269}}{\mathbf{Work\ \ Area\ \ Quantity}} \quad \text{(Equation 7.10)}$$

7.5 SUMMARY OF FINDINGS ON DRIVER ANALYSES

Table 7.14 summarizes the results of driver analysis for Pavement-related Work Items. Project type was not analyzed due to insufficient data. None of the investigated Candidate Drivers at the project- and Work Zone- level was found to significantly affect Production Rate. For Candidate Drivers at the Work Item-level, Work Area Quantity was identified as a driver for the three targeted Pavement-related Work Items. Length of Work Area was identified as a Production Rate driver of Slip-form concrete pavement. In addition, Course type is a Production Rate driver of Hot mix asphalt pavement, and Configuration is a Production Rate driver of Conventional form concrete pavement construction.

Table 7.15 lists the drivers identified as having a significant Production Rate impact for major Pavement-related Work Items. A multiple regression model was developed for Hot mix asphalt pavement to determine the interaction effects of the identified drivers. For Slip-form concrete pavement, multiple regression analysis was not applicable because a high correlation was found between its drivers. For Conventional form concrete pavement, insufficient data limited the development of a multiple regression model.

Table 7.14 Summary of Results of Driver Analyses

	Candidate Drivers	Hot Mix Asphalt Pavement	Slip-from Concrete Pavement (CRCP)	Conventional Form Concrete Pavement
Project Level	Project Type	⊕	⊕	⊕
	Project Location	○	○	○
	Traffic Flow	○	○	○
	Project Complexity	○	○	○
	Accelerated Construction Provision	○	○	○
	Contractor Management Skill	○	○	○
Work Zone Level	Work Zone Accessibility	○	○	○
	Work Zone Congestion	○	○	○
	Work Zone Land Slope	○	○	○
Work Item Level	Work Area Quantity	●	●	●
	Length of Work Area		●	
	Thickness		○	○
	Width of Work Area		○	
	Course Type	●		
	Main Lane vs. Non-main Lane	○		
	Type of Concrete Pavement		⊕	
	Configuration			●

●: Driver found to be statistically significant
○: Investigated but not statistically significant
⊕: Insufficient data for analysis

Table 7.15 Summary of Identified Production Rate Drivers

Work Item	Drivers	Type of Regression Model used for Analysis	Regression Analysis/T Test	Multiple Regression Analysis
Hot Mix Asphalt Pavement	Work Area Quantity	Log model	R^2= 0.432	R^2= 0.488
	Course Type	********	P=0.093	Adjusted R^2= 0.452
Slip-form Concrete Pavement	Work Area Quantity	Log model	R^2= 0.653	*None
	Length of Work Area	Log model	R^2= 0.356	
Conventional Form Concrete Pavement	Work Area Quantity	Log model	R^2= 0.511	**None
	Configuration	********	P<0.001	

*None: Because the two drivers are highly correlated, multiple regression analysis is not applicable.
**None: The sample size was not sufficient for multiple regression analysis.

CHAPTER VIII: CONCLUSIONS OF THIS RESEARCH

The purpose of this study was to investigate realistic Production Rates, and to identify drivers known at the design stage which influence Production Rates as well as to quantify their effects for seven Work Items in Earthwork and Pavement construction. Based on the findings in this study, the highway construction industry can improve the reliability of their Production Rates database, which should lead to more reasonable Contract Time estimation. Since the drivers discussed in this study were those that should be available at the design stage, more accurate estimation should be possible.

8.1 CONCLUSIONS

Except for Flexible base, the observed Production Rates collected from on-going projects were significantly different from the Production Rates in the CTDS. The CTDS Production Rates for most major Work Items in Earthwork and Pavement construction were found to be too optimistic. Sizable variation of observed Production Rates leads one to believe that Production Rate estimation can be far from realistic rates without consideration of statistically Significant Drivers. The Production Rate data found from historical records did not contain sufficient information to explain the variation in Production Rates.

The drivers significantly influencing Production Rates of the seven targeted Work Items in Earthwork and Pavement construction were identified and their effects were quantified. Table 8.1 displays the identified significant Production Rate drivers for seven targeted Work Items as well as the sensitivity factors considered in the CTDS. Work Area Quantity was found to have a positive relationship with the Production Rates of all seven targeted Work Items in Earthwork and Pavement construction. One reason could be that all seven targeted Work Items are highly repetitive in their nature. When a Work Area involves a large quantity of work, Production Rates are higher due to learning effects. Another reason could be that contractors are more willing to contribute more effort on engineering and more resources to a larger quantity of work in order to reduce total cost and construction time. A final reason could be that productive hours per working day are higher when a Work Area involves a large quantity.

Although the CTDS study indicates that Soil Condition, Location and Traffic Condition are sensitive to the respective Work Items (refer to Table 8.1), this research did not find that they were statistically significant.

For Lime-treated sub-grade, Aggregate base, and Slip-form concrete pavement, the results of correlation tests of identified drivers showed that Length of Work Area was highly correlated with Work Area Quantity. It is obvious that longer Work Area implies larger Work Area Quantity. Therefore, the effects of Work Area Quantity and Length of Work Area should not be considered concurrently during Production Rate estimation.

Table 8.1 Work Items vs. Significant Drivers of this Research and the CTDS

Research		CTDS	
Targeted Work Items	**Significant Drivers**	**Work Items**	**Sensitivity Factors**
Earth Excavation	Work Area Quantity	**Earth Excavation**	Quantity of Work Soil Condition
Embankment	Work Area Quantity Work Zone Congestion	**Embankment**	Quantity of Work Soil Condition
Lime Ttreated Sub-grad	Work Area Quantity Length of Work Area	**Lime Stablization**	Quantity of Work Soil Condition
Flexible Base	Work Area Quantity Length of Work Area	**Flexible Base Material**	Quantity of Work Location
Cement Treated Base	Work Area Quantity Length of Work Area	**Cement Treated Base Material**	Quantity of Work Soil Condition
Hot Mix Asphalt Pavement	Work Area Quantity	**Hot Mix Asphalt Base**	Quantity of Work Location
	Course Type	**Hot Mix Asphalt Surface**	Quantity of Work Traffic Condition
Slip-from Concrete Pavement	Work Area Quantity Length of Work Area	**Concrete Paving**	Quantity of Work
Conventional Form Concrete Pavement	Work Area Quantity Configuration		Location

Course type is a Production Rate driver of Hot mix asphalt pavement construction. The difference in quality requirements of Base courses and Surface courses could be the main reason for the difference in average Production Rates between the two Course types. Surface courses are usually constructed with a higher standard of quality than Base courses. To reach a higher standard of quality control, slower paving speed in order to achieve more precise grading and compacting is applied to Surface course construction.

Configuration of concrete pavement was a significant Production Rate driver on Conventional form concrete pavement construction. Curve(s) or sharp angle(s) increases the technical complexity for formwork and rebar installation. This is the most likely reason for lower Production Rates for the Conventional form concrete pavement with any curve or sharp angle.

Once the drivers of Production Rates for the seven targeted items were identified and their effects were found, their correlations were also explored. Based on the findings in this study the Production Rates of the seven targeted Work Items could be estimated. However, there are some limitations to the application.

First, the effects of drivers on Production Rates should only be used as a reference to estimate Production Rates. The effects on Production Rates from multiple drivers are not equivalent to the sum of the effects of each driver. Therefore, designers should carefully evaluate the combined effects of all drivers during Production Rate estimation.

Second, because of the presence of a maximum Production Rate, a non-linear model was more appropriate than a linear model to model Production Rates for construction activities. Furthermore, the limited number of data points may not be representative for all applications. Therefore, the limitations of the model must be recognized.

Third, this study is limited to Production Rate estimation for Contract Time estimation. In other words, the scope for measuring Production Rates would be different for cost management purposes.

8.2 RECOMMENDATIONS

The Production Rate data of seven major earthwork-and pavement-related Work Items have been collected for this study. Future research should collect data on additional TxDOT Work Items frequently on the critical path, such as rock excavation, and concrete curb and gutter. In addition, a reliable Production Rate database should be created to facilitate Contract Time estimation.

Significant Drivers known at the design stage were identified for each targeted Work Item. Future studies should seek to better understand remaining sources of Production Rate variability such as weather impact and operator skill. Moreover, lead and lag time information should be investigated to enhance information for time-estimating.

APPENDICES

Appendix A. Questionnaire for Selecting Work Items for the Study

Name : ____________________

District : ____________________ Position : ________________________

Site/Office Address :____

Phone Number : ____________________ E-mail Address : ________________________

Please check as you think it is most appropriate

Pay Items	**Definitely Track?**	**Degree of Variability in Crew Productivity**			**How often On or Near Critical Path**			
	Yea/**N**o	**L**ow	**M**oderate	**H**igh	**Rarely**	**Sometimes**	**Often**	**Usually**
Initial traffic control	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Detour	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
ROW Preparations								
Clear & Grub	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Remove old structure(small)	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Remove old pavement	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Remove old curb & gutter	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Remove old sidewalks	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Remove old drainage/utility structures	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Major structure demolition	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually

Appendix A. Questionnaire for Selecting Work Items for the Study (Cont'd)

Pay Items	**Definitely Track?**	**Degree of Variability in Crew Productivity**			**How often On or Near Critical Path**			
Excavation/embankment								
Earth excavation	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Rock excavation	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Embankment	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Drainage structures/storm sewers								
Pipe	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Box culverts	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Inlets & Manholes	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Bridge Structures								
Erect temporary bridge	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Bridge demolition	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Cofferdams	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Piling	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Footings	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Columns, caps & bents	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Wingwalls	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually

Appendix A. Questionnaire for Selecting Work Items for the Study (Cont'd)

Pay Items	Definitely Track?	Degree of Variability in Crew Productivity			How often On or Near Critical Path			
	Yea/**N**o	**L**ow	**M**oderate	**H**igh	**Rarely**	**Sometimes**	**Often**	**Usually**
Beams (erection only)	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Bridge deck (total depth)	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Bridge curb/walk	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Bridge handrail	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Remove temporary bridge	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Retaining walls	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Base Preparations								
Lime stabilization	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Flexible base material	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Cement treated base material	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
New curb & gutter	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Hot mix asphalt base	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Concrete paving	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Hot mix asphalt surface	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually

Appendix A. Questionnaire for Selecting Work Items for the Study (Cont'd)

Pay Items	Definitely Track?	Degree of Variability in Crew Productivity			How often On or Near Critical Path			
	Yea/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
Permanent signing & traffic signals								
Small signs	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
Overhead signs	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
Major traffic signals	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
Seeding & Landscape	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
Permanent pavement markings	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
Final clean up	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
Others								
___________________________	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
___________________________	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
___________________________	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually

Your Comment (*We appreciate your comment*)

Are you interested in continued participation in this study? Yes No

Thank You.

Appendix B. Results of the Survey for Selecting Work Items to be Tracked

Results of the Survey for Selectiing Work Items to be tracked

Work Items	Definitely Track? - 'Yes' Response													Total of 'Yes'
	Bob. H.	Carlos C.	Doug W.	Dan D.	Mike L.	Harry P.	Mario R.G.	David H.	Pat W.	Mike B.	Duane S.	Tom N.	Mike C.	
Initial traffic control					Yes		Yes	Yes	Yes		Yes	Yes	Yes	7
Detour					Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	8
ROW Preparations														
Clear & Grub					Yes		Yes	Yes	Yes	Yes			Yes	6
Remove old structure(small)							Yes	Yes	Yes			Yes		4
Remove old pavement					Yes		Yes	Yes	Yes		Yes	Yes		6
Remove old curb & gutter							Yes	Yes	Yes					3
Remove old sidewalks							Yes	Yes	Yes					3
Remove old drainage/utility structures		Yes			Yes		Yes	Yes	Yes					5
Major structure demolition		Yes			Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	9
Excavation/embankment														
***Earth excavation**	Yes				Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	9
Rock excavation	Yes				Yes		Yes	Yes		Yes			Yes	6
***Embankment**	Yes	Yes			Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	10
Drainage structures/storm sewers														
Pipe	Yes				Yes		Yes	Yes	Yes	Yes	Yes	Yes		8
Box culverts	Yes	Yes			Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	10
Inlets & Manholes	Yes				Yes		Yes	Yes	Yes	Yes	Yes	Yes		8
Bridge Structures														
Erect temporary bridge		Yes					Yes		Yes					3
Bridge demolition		Yes			Yes		Yes	Yes	Yes		Yes	Yes		7
Cofferdams					Yes		Yes		Yes		Yes			4
Piling		Yes			Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	9
Footings					Yes		Yes	Yes	Yes	Yes	Yes		Yes	7
Columns, caps & bents	Yes	Yes			Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	10
Wingwalls		Yes			Yes			Yes	Yes	Yes	Yes		Yes	7
Beams (erection only)		Yes			Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	9
Bridge deck (total depth)	Yes	Yes			Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	10
Bridge rail	Yes	Yes			Yes		Yes	Yes	Yes	Yes	Yes	Yes		9
Bridge curb/walk							Yes	Yes	Yes					3
Bridge handrail		Yes						Yes						2
Remove temporary bridge		Yes							Yes	Yes	Yes			4
Retaining walls	Yes	Yes			Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	10
Base Preparations														
***Lime stabilization**	Yes				Yes		Yes		Yes	Yes	Yes	Yes		7
***Flexible base material**	Yes				Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	9
***Cement treated base material**	Yes	Yes			Yes		Yes		Yes	Yes	Yes			7
New curb & gutter	Yes				Yes		Yes	Yes	Yes		Yes		Yes	7
***Hot mix asphalt base**	Yes				Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	9
***Concrete paving**	Yes	Yes			Yes		Yes	Yes	Yes	Yes	Yes	Yes		9
***Hot mix asphalt surface**	Yes	Yes			Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	10
Permanent signing & traffic signals														
Small signs					Yes			Yes	Yes					3
Overhead signs		Yes			Yes		Yes	Yes	Yes		Yes	Yes		7
Major traffic signals					Yes		Yes	Yes	Yes		Yes	Yes	Yes	7
Seeding & Landscape					Yes			Yes	Yes					3
Permanent pavement markings		Yes			Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	9
Final clean up		Yes			Yes			Yes	Yes		Yes		Yes	6
Total of 'Yes'	17	21	0	0	35	0	36	37	40	25	31	25	22	
Others		Traffic Switches, Temporary Striping, CTB Move & Reset			Utility Installation /adjustment				Drill Shaft/ Surface Treatment	Planning Hot Mix Pav't	Drill Shaft			

Appendix C. Project-Level Data Collection Tool

Production Rate Tracking : Project level

CCSJ # :

Project Length :

District :

Prime Contractor:

% of Project Completion : %

Highway # :

Project ID:

Station Range :

City/County :

Contract Amount : $ Million

Project(Construction) Period : --- (Calandar/Working days)

Work Items to be tracked:

Item #	Work Item	Unit	Approx. Total Quantity	Scheduled Start Date	Scheduled End Date	Sub- Contracted?	Comments
						Yes ☐ No	
						Yes ☐ No	
						Yes ☐ No	
						Yes ☐ No	
						Yes ☐ No	
						Yes ☐ No	
						Yes ☐ No	
						Yes ☐ No	
						Yes ☐ No	
						Yes ☐ No	

Please, fill out next page.

Appendix C. Project-Level Data Collection Tool (Cont'd)
Project Level Variables Evaluation

Project CCSJ:

Variable		Unit	Optional Values				
Project Type			□ Seal Coat	□ Overlay	□ Rehabilitate Existing Road	□ Convert Non-Freeway to Freeway	
			□ Widen Freeway	□ Widen Non-Freeway	□ New Location Freeway	□ New Location Non-Freeway	
			□ Interchanges	□ Bridge Widening/ Rehabilitation	□ Bridge Replacement/ New Bridge	□ Upgrade Freeway to Standards	□ Upgrade Non-Freeway to Standards
Location			□ Rural	□ Urban	□ Metro		
Traffic Flow			□ Rarely congested	□ Only rush hours congested	□ Most hours congested		
Traffic Count (ADT)		Veh./ Day	□ < 5 K	□ 5 K ~ 20 K	□ > 20 K		
Weather	Annual Precipitation	/Year	□ < 15"	□ 15"~40"	□ > 40"		
	Winter Season Length		□ Costal	□ Central & South Texas	□ North Texas	□ Panhandle & West Texas	
% of Construction Completion at 1st Data Collection Date		%	□ 0-30	□ 30-70	□ 70-100		
Size : Construction Contract Amount		$	□ <5M	□ 5M ~ 20 M	□ 20M ~ 50 M	□ >50M	
Technical Complexity			□ Simple	□ Moderate	□ Complex		
Contract	Contract Day		□ Calendar Day	□ Working Day			
	Accelerated Constrcution Provision		□ None	□ Incentive Using Contract Administrative Cost	□ Milestones with Incentives/ Disincentives		
			□ Substantial Completion I/D	□ Lane Rental Disincentive	□ A+B Provisions		
	Liquidated damages	$/Day	□ < 300	□ 300~3K	□ 3K~6K	□ 6K~12K	□ > 12K
Soil types			□ Loose	□ Stiff	□ Rocky		
Local site Drainage Effectiveness	Clay Content (Plastic Soils)		□ Low	□ Moderate	□ High		
	Land Slope		□ Flat	□ Moderate	□ Steep		
	Water Table Depth below Grade		□ < 4'	□ 4' ~ 10'	□ > 10'		
Scheduling Technique Used			□ Bar Chart	□ CPM (Not Resource-loaded)		□ CPM (Resource-loaded)	
Work Schedule	Days per Week (typical)	Day/Week	□ 4	□ 5	□ 6	□ 7	
	Hours per Day(typical)	Hours/Day	□ 8	□ 10	□ 12	□ 2 Shifts	
Contract Admin. System			□ C.I.S.	□ Site Mgmt.			
CMS (Contractor Management Skill)			□ Good	□ Average	□ Poor		

Appendix D. Work Zone & Work Item -Level Data Collection Tool

Production Rate Tracking: Work Zone Level

Work Zone & Work Item Assessed

Project ID: ___________________ District: ______________________

Work Item (No.): ____

Work Zone Description/Sketch:

Description:	Sketch
____ ____	
Typical Workday Start Time: ________________________	
Typical Workday Stop Time: ________________________	
Is observed Work Item on critical path? ☐ Yes ☐ No	▪ No. indicates the No. of Traffic lines
Workers are from: ☐ Union ☐ Non-Union	▪ Double line indicates that WZ is not
How much quantity included in the Work Area: ____	affected at all by its side of traffic.

Work Zone Level Variables Evaluation

Variable		Characterization				Comment
1	WZ Accessibility	Difficult	Moderate	Easy	Not applicable	
2	WZ Construction Congestion	Severe	Moderate	Minor	Not applicable	
3	Work Zone Site Drainage Effectiveness	Easily Flooded	Moderate	Quickly Drained	Not applicable	
3.1	Clay Content in Soil	High	Moderate	Low	Not applicable	
3.2	Land Slope	Steep	Moderate	Flat	Not applicable	
3.3	Water Table Depth Below Grade	<4’	4’~10’	>10’	Not applicable	

☐ Check if data Collection completed

Appendix D. Work Zone & Work Item -Level

Data Collection Tool (Cont'd)

Production Rate Tracking: Work Item Level

Observation Record Recorder: ________________

Date:	
Approximate % of Completion	
Completion Status: Fully Labeled Sketch and Description	

Quantity Completed		Unit	

Appendix D. Work Zone & Work Item -Level

Data Collection Tool (Cont'd)

Production Rate Tracking (Work Item Level)

Observation Record

Resource Efforts for Work Item			
Crew			
Crew Type	Average Skill Level		Crew Size
	Novice Typical Experienced		
	Novice Typical Experienced		
	Novice Typical Experienced		
	Novice Typical Experienced		
Equipment			
Equipment Piece	Equipment Size	Number in Operation	

Note: #1~#5 is the observation number.

Appendix D. Work Zone & Work Item -Level

Data Collection Tool (Cont'd)

Production Rate Tracking Calendar (Work Item Level)

Sunday		Monday		Tuesday		Wednesday		Thursday		Friday		Saturday	
/	I II III VI	/		/		/		/		/		/	
/		/		/		/		/		/		/	
/		/		/		/		/		/		/	
/		/		/		/		/		/		/	
/		/		/		/		/		/		/	

I: Observation #, **II**: X, ○ or ⊖, **III**: Indication except X, ○ and ⊖, **VI**: Comment No.

Total Working Days: _______________

Indication

T - #: **T**his Observation #	**H**: **H**oliday or Day Off
W: **W**eather day (< 2 Hrs of work)	**S**: Work Day With **S**ome Weather Effect
N: U**N**workable Soil Condition	**I**: **I**ncomplete Crew
E: **E**quipment Downtime/not Available	**M**: **M**aterial Unavailable
U: **U**tility Conflicts	**F**: Un**F**oreseen Condition
C: **C**onstruction Accident	**A**: Traffic **A**ccident
O: **O**vertime	**D**: Other **D**elay (specify in comments)

○ : Normal Working Day	⊖ : Working Day with Delay	X: Non Working Day

Comments:	
1	
2	

Appendix D. Work Zone & Work Item -Level

Data Collection Tool (Cont'd)

Production Rate Tracking Calendar (Work Item Level)

Comments (Continued):	
3	
4	
5	
6	
7	
8	
9	
10	
11	
12	
General Comment	

Appendix E. Work Item Sheets

<table>
<tr><th>Work Item</th><th>Sub-Item</th><th colspan="2">Work Item #</th><th>Unit of Measurement</th></tr>
<tr><td>Excavation</td><td>Earth Excavation</td><td colspan="2">110</td><td>CY/Crew Day</td></tr>
<tr><td>SCOPE</td><td colspan="2">Included</td><td colspan="2">Not Included</td></tr>
<tr><td colspan="3">- Removing top soil
- Excavation from original elevation to the elevation which is at least 6” below the required sub-grade elevation
- Disposal of material</td><td colspan="2">- Survey & Layout
- Access road construction and maintenance
- Unsuitable material replacement
- Reshaped by blade and then sprinkled and rolled for sub-grade surface (about 6” depth)
- Temporary drainage maintenance
- Shaping slop
- Rock</td></tr>
<tr><td rowspan="2" colspan="2">PRODUCTIVITY FACTOR
(Work Item)</td><td colspan="3">- Construction Type(Haul to Waste, Cut to Fill), (Note:________________________)
- Haul road distance (Specify: ______________________________________)</td></tr>
<tr><td colspan="3">- Equipment number/Equipment size/Soil Type/Clay content in soil</td></tr>
<tr><td rowspan="2">NODE</td><td>Starting</td><td colspan="3">- Remove top soil.
- Starting the excavation of any working phase.</td></tr>
<tr><td>Ending</td><td colspan="3">- Sub-grade surface is completed.
- Reach the anticipated elevation of the working phase</td></tr>
<tr><td rowspan="2" colspan="2">A Crew Definition</td><td colspan="3">- Equipment: 1 Excavator (2CY Bucket), Trucks (Number is according to the distance from disposal field to Work Zone and traffic condition.)</td></tr>
<tr><td colspan="3">Comments;
Verified ________</td></tr>
</table>

- *Node; In a special case, a data collector can judge the Starting and the Ending Node based on his/her professional experience.*

Appendix E. Work Item Sheets (Cont'd)

<table>
<tr><th colspan="2">Work Item</th><th>Sub-Item</th><th>Work Item #</th><th>Unit of Measurement</th></tr>
<tr><td colspan="2">Embankment</td><td>Embankment</td><td>132</td><td>CY/Crew Day</td></tr>
<tr><td>SCOPE</td><td colspan="2">Included</td><td colspan="2">Not Included</td></tr>
<tr><td colspan="3">(Construction of roadway embankments, levees and dykes or any designated section of the roadway)
- Placing materials
- Spread material
- Sprinkling
- Compaction</td><td colspan="2">- Survey & Layout
- Constructing access road
- Temporary drainage maintenance</td></tr>
<tr><td rowspan="2">PRODUCTIVITY FACTOR
(Work Item)</td><td colspan="4">- Material Type (Type A, Type B, Type C, Type D), (Note: _________________)
- Density Requirement (Ordinary Compaction, Density Control)
- Construction Type(Borrow to Fill, Cut to Fill), (Note: ________________________)
- Slope (Steep, Moderate, Flat), (Note: _______________________________________)</td></tr>
<tr><td colspan="4">- Equipment number/Equipment size/Work Zone Congestion/Clay content in soil/Work Zone drainage effectiveness</td></tr>
<tr><td rowspan="2">NODE</td><td>Starting</td><td colspan="3">- Place the first load of embankment material.</td></tr>
<tr><td>Ending</td><td colspan="3">- Sub-grade surface is completed. .
- Reach the elevation of the working phase if there are more than one phases of embankment</td></tr>
<tr><td rowspan="2">A Crew Definition</td><td colspan="4">- Equipment: 1~2 Dozer, 1 Compactor</td></tr>
<tr><td colspan="4">Comments;
Verified ________</td></tr>
</table>

- *Node; In a special case, a data collector can judge the Starting and the Ending Node based on his/her professional experience.*

Appendix E. Work Item Sheets (Cont'd)

Work Item	Sub-Item	Work Item #	Unit of Measurement
Lime-Treated for materials used as sub-grade	**Lime-Treated for materials used as sub-grade**	**260**	**SY/Crew Day**

SCOPE	Included	Not Included
	- Cutting & pulverizing - Spread Lime - Mixing - Sprinkling or aerating - Compaction - Finishing - 1^{ST} curing and 2^{nd} mixing	- Survey & layout - Equipment move in - Transport material - Curing (after finishing) - Density tests - Setup blue top

PRODUCTIVITY FACTOR **(Work Item)**		- **Number of Mixing (*Specify:* ____)** - **Lift Height (Specify: ____)** - **Type C Lime Used (Yes, No) (*Note:* __________________________________)** - **Total Length Ready For Work (*Specify:* ______________________________)** - **Average Width of Work Area (*Specify:* ______________________________)** - **Slope (Steep, Moderate, Flat), (Note: ________________________________)**
		- Work Zone Congestion/Soil Type/# of working days only for curing/# of non-working days on curing
NODE	**Starting**	- Spread lime or cut & pulverize sub-grade.
	Ending	- Finishing sub-grade surface is completed.
A Crew Definition		- Equipment: 1 Stabilizer, 1 Motor Grader, 1 or 2 Spreader, 1 Sheep-foot Roller, 1 Flat Roller
		Comments; **Verified ________**

- *Node; In a special case, a data collector can judge the Starting and the Ending Node based on his/her professional experience.*

Appendix E. Work Item Sheets (Cont'd)

Work Item	Sub-Item	Work Item #	Unit of Measurement
Aggregate Base Course	**Aggregate Base Course**	**247, 262, 263, 275, 276**	**LIFT-SY/Crew Day**

SCOPE	Included	Not Included
	- Placing materials - Spread uniformly & shaping - Blade & shaping - Sprinkle - Compact - Dry-out (if required) -	- Survey & layout - Shaping the sub-grade or existing roadbed - Stockpiled - All material tests excluded - Curing (Flexible Base: Directed by Engineers, usually 2 days; CTB: 72 hours) - Density tests - Rework caused by failing to achieve required density

PRODUCTIVITY FACTOR **(Work Item)**		- **Lift Height (*Specify:* ___________________________)** - **Total Lift Length (*Specify:* _____________________)** - **Average Width (*Specify:* _______________________)** - **Number of Lifts (*Specify:* ______________________)** - **Type of treatment (None, Lime treatment, Portland Cement), (*Note:* ________)** - **Treatment Mixing Method (Plant mixing, Roadway mixing), (Note: _________)** - **Slope (Steep, Moderate, Flat), (Note: ___________________________________)**
		- Location/ Soil Type/ Work Zone Congestion
NODE	**Starting**	- Place the first load of base material.
	Ending	- Finishing a lift of base course is completed.
A Crew Definition		- Equipment: 1 Motor Grader, 1~2 Steel Roller, 1 Water Truck, Trucks (Number is according to the distance from Work Zone to material resource)
		Comments; **Verified ________**

- *Node; In a special case, a data collector can judge the Starting and the Ending Node based on his/her professional experience.*

Appendix E. Work Item Sheets (Cont'd)

<table>
<tr><th>Work Item</th><th colspan="2">Sub-Item</th><th>Work Item #</th><th>Unit of Measurement</th></tr>
<tr><td>Hot Mix Asphalt</td><td colspan="2">Hot Mix Asphaltic Concrete Pavement, Asphalt Stabilized Base</td><td>340, 345</td><td>Ton/Crew Day</td></tr>
<tr><td>SCOPE</td><td colspan="2">Included</td><td colspan="2">Not Included</td></tr>
<tr><td colspan="3">- Lay Hot Mix Asphalt
- Compaction (Roller or lightly oiled tamps)</td><td colspan="2">- Survey and layout
- Transport materials
- Cleaning surface before applying for tack coat
- Shoot tack coat (if tack coat required)
- Mixing materials in the plant
- Equipment setup</td></tr>
<tr><td colspan="2" rowspan="2">PRODUCTIVITY FACTOR
(Work Item)</td><td colspan="3">- Thickness of Lifts (Specify: ____)
- (Bond Breaker, Base Course, Surface) construction, (Note: ______________)
- Asphalt Plant Capacity (Production Rate) (Specify: _______________tons/hr)
- (Machine Laid, Blade Laid), (Note: _________________________________)
- Slope (Steep, Moderate, Flat), (Note: ________________________________)</td></tr>
<tr><td colspan="3">- Traffic Condition/ Location</td></tr>
<tr><td rowspan="2">NODE</td><td>Starting</td><td colspan="3">- Place the first load of Hot Mix Asphalt material.</td></tr>
<tr><td>Ending</td><td colspan="3">- Complete compaction.</td></tr>
<tr><td colspan="2" rowspan="2">A Crew Definition</td><td colspan="3">- Labors: One crew (6-8)
- Equipment: 1 Lay down Machine, 1 Pneumatic Roller, 5 Trucks</td></tr>
<tr><td colspan="3">Comments;
Verified ________</td></tr>
</table>

- *Node; In a special case, a data collector can judge the Starting and the Ending Node based on his/her professional experience.*

Appendix E. Work Item Sheets (Cont'd)

<table>
<tr><th>Work Item</th><th colspan="2">Sub-Item</th><th>Work Item #</th><th>Unit of Measurement</th></tr>
<tr><td>Concrete Paving</td><td colspan="2">Slip-form</td><td>360-1</td><td>SY/Crew Day</td></tr>
<tr><td>SCOPE</td><td colspan="2">Included</td><td colspan="2">Not Included</td></tr>
<tr><td colspan="3">- Setting string line
- Placing dowels
- Installing reinforcing steel
- Placing joint assemblies
- Initial equipment setup
- Placing concrete
- Finishing</td><td colspan="2">- Survey & Layout
- Surface preparation
- Equipments move in
- Ride quality test
- Core test
- Unloading reinforcing steel
- Curing
- Saw cutting</td></tr>
<tr><td colspan="2" rowspan="2">PRODUCTIVITY FACTOR
(Work Item)</td><td colspan="3">- (Continuously reinforced concrete pavement, Jointed concrete pavement, Non-reinforced concrete pavement), (Note: ________________________________)
- Thickness of Concrete Pavement (Specify: ____________________________)
- Total Length Ready for Slip (Specify: ______________________________)
- Width of Pass (Specify: ____)
- Number of Moving Slip-Form Paver (Specify: _______________________)
- Quantity of Concrete Poured (Specify: ______________________________)
- Slope (Steep, Moderate, Flat) (Note: _______________________________)</td></tr>
<tr><td colspan="3">- Location</td></tr>
<tr><td rowspan="2">NODE</td><td>Starting</td><td colspan="3">- Set string line.</td></tr>
<tr><td>Ending</td><td colspan="3">- Complete concrete placement.</td></tr>
<tr><td colspan="2" rowspan="2">A Crew Definition</td><td colspan="3">- Labors: One crew for reinforcing bar (8-10), One crew for concrete feeding and placing (6-8)
- Equipment : 1 Slip-form Paver, 1 Material Transfer</td></tr>
<tr><td colspan="3">Comments;
Verified ________</td></tr>
</table>

- *Node; In a special case, a data collector can judge the Starting and the Ending Node based on his/her professional experience.*

Appendix E. Work Item Sheets (Cont'd)

<table>
<tr><th colspan="2">Work Item</th><th>Sub-Item</th><th>Work Item #</th><th>Unit of Measurement</th></tr>
<tr><td colspan="2">Concrete Paving</td><td>Conventional Hand-form</td><td>360-2</td><td>SY/Crew Day</td></tr>
<tr><td>SCOPE</td><td colspan="2">Included</td><td colspan="2">Not Included</td></tr>
<tr><td colspan="3">- Formwork
- Installing reinforcing steel
- Placing concrete
- Spread and finishing</td><td colspan="2">- Survey & Layout
- Surface preparation
- Cutting & bending Reinforcing steel
- Core test
- Curing
- Removing formwork</td></tr>
<tr><td colspan="2" rowspan="2">PRODUCTIVITY FACTOR
(Work Item)</td><td colspan="3">- Spread roller used (Yes, No), (Note: ___________________________________)
- Slope (Steep, Moderate, Flat) (Note: ___________________________________)
- Shape (Simple Configuration, With any Curve and Sharp Angle)(Note: _____)</td></tr>
<tr><td colspan="3">- Crew size/Work Zone congestion</td></tr>
<tr><td rowspan="2">NODE</td><td>Starting</td><td colspan="3">- Start to setup formwork</td></tr>
<tr><td>Ending</td><td colspan="3">- Complete concrete placement.</td></tr>
<tr><td colspan="2" rowspan="2">A Crew Definition</td><td colspan="3">- Labors: One crew for formwork (3-4), One crew for reinforcing bar (6-8), One crew for concrete pouring (6-10)</td></tr>
<tr><td colspan="3">Comments;
Verified ________</td></tr>
</table>

- *Node; In a special case, a data collector can judge the Starting and the Ending Node based on his/her professional experience.*

Appendix F. Safety Protocol

Safety Protocol for Construction Site Visits

(TXDOT Project 0-4416)

READ, FAMILIZE and OBEY THIS SAFETY PROTOCOL BEFORE SITE VISIT

Ensure compliance with all regulations concerning the standard safety procedures of TxDOT and site.

Site protocol

Arrival: On each and every visit, the GRA must report to field office and gain permission to enter the site.

Departure: Report back to the field office on departure.

Vacant Sites: If there are no site representatives on site, then access is prohibited.

Instructions: GRA must follow any instructions given to them whilst on site, from the site representative or TxDOT personnel.

Safety Procedures

Responsibility
Avoiding accidents: GRA can avoid accidents by concentrating and thinking before acting. Remember that acting on impulse and taking shortcuts causes many accidents.

Parking & Transportation: GRA should park near the field office and go to job site with TxDOT personnel.

Clothing
Safety vest: Wear safety vest all the times in the job site.

Hardhats: Wear safety hardhats all the times in the job site.

Footwear: Wear steel-toed boots if required.

Appendix F. Safety Protocol (Cont'd)

Hearing protection: Ear protection should be worn if required.

Safety glass: Wear safety glass in required area.

Loose clothing: Do not wear loose clothing.

Moving around the site

Barricades: Do not lean over or go beyond any protective handrails or barricades.

Openings: Be careful where you walk. Pay attention to openings, barriers, protective covers and changes in levels.

Access: Use correct access at all times.

Restricted areas: Keep out of restricted areas.

Movement: Running on any part of the site is prohibited. Never walk backwards in a construction area. Do not jump from equipment, platforms or scaffolds. Do not stand or walk under any loads being lifted.

Weather: Beware of slippery surfaces (particularly after or during rain). Be careful in windy weather.

Behaviors on-site: Restrict communication with workers unless it is necessary for the research.

Traffic: Be aware of moving equipment and vehicles. Traffic rules should be obeyed and strict attention should be paid to all warning signs at all times.

Taking pictures: GRA can freely take the pictures on the surveyed Work Items unless it is restricted.

Appendix G. General Information of Investigated Projects

Project ID	District	Prime	Contract Amount	Project Type	Location	Contract Amount Range	Project Complexity	Accelerated Construction Provision	Contract Management Skill
P1	D1	GC 11	10.90	Widen Nonfreeway	Urban	5 ~ 20 Million	Simple	None	Good
P2	D1	GC 22	29.60	Widen Freeway	Metro	20~50 Million	Complex	None	Good
P3	D1	GC 22	18.90	Widen Freeway	Metro	5 ~ 20 Million	Complex	None	Average
P4	D1	GC 8	35.90	Upgrade Nonfreeway To Standards	Urban	20~50 Million	Complex	Milestones with Incentives/Discentive	Average
P5	D2	GC 3	20.00	Covert Nonfreeway to Freeway	Urban	20~50 Million	Moderate	None	Good
P6	D2	GC 12	9.00	Covert Nonfreeway to Freeway	Urban	5 ~ 20 Million	Moderate	None	Good
P7	D3	GC 14	87.80	Interchanges	Metro	>50 Million	Complex	None	Average
P8	D3	GC 14	50.49	Covert Nonfreeway to Freeway	Metro	>50 Million	Moderate	None	Good
P9	D3	GC 5	6.80	Widen Nonfreeway	Urban	5 ~ 20 Million	Moderate	None	Good
P10	D3	GC 2	4.50	Widen Nonfreeway	Rural	5 ~ 20 Million	Simple	None	Good
P11	D4	GC 7	8.55	Widen Freeway	Urban	5 ~ 20 Million	Moderate	None	Good
P12	D4	GC 17	12.00	Widen Nonfreeway	Urban	5 ~ 20 Million	Moderate	None	Average
P13	D4	GC 6	8.60	Rehailitate Existing Road	Urban	5 ~ 20 Million	Simple	Substantial Completion I/D	Good
P14	D4	GC 22	75.13	Upgrade Freeway to Standards	Urban	>50 Million	Complex	None	Average
P15	D4	GC 18	17.00	Widen Nonfreeway	Rural	5 ~ 20 Million	Moderate	None	Good
P16	D4	GC 22	261.00	Interchanges	Metro	>50 Million	Complex	Milestones with Incentives/Discentive	Good
P17	D4	GC 6	8.30	Rehailitate Existing Road	Urban	5 ~ 20 Million	Simple	Substantial Completion I/D	Good
P18	D5	GC 20	16.10	Upgrade Freeway to Standards	Urban	20~50 Million	Moderate	None	Good
P19	D5	GC 22	15.20	Upgrade Freeway to Standards	Urban	20~50 Million	Moderate	None	Good
P20	D5	GC 20	9.60	Upgrade Freeway to Standards	Urban	20~50 Million	Moderate	None	Good
P21	D5	GC 19	3.77	Bridge Replacement/New Bridge	Rural	< 5 Million	Moderate	None	Good
P22	D5	GC 20	23.29	New Location Freeway	Urban	20~50 Million	Moderate	None	Good
P23	D5	GC 20	80.90	Upgrade Nonfreeway To Standards	Metro	20~50 Million	Complex	Milestones with Incentives/Discentive	Good
P24	D5	GC 19	16.60	Widen Freeway	Rural	5 ~ 20 Million	Moderate	None	Average
P25	D5	GC 13	1.52	Bridge Widening/Rehibilitation	Rural	< 5 Million	Simple	None	Average
P26	D5	GC 20	104.00	Widen Freeway	Urban	>50 Million	Moderate	Milestones with Incentives/Discentive	Good
P27	D6	GC 10	47.00	Covert Nonfreeway to Freeway	Urban	20~50 Million	Complex	Incentive using contract administrative cost	Average
P28	D6	GC 1	7.43	Rehailitate Existing Road	Rural	5 ~ 20 Million	Moderate	None	Average
P29	D7	GC 4	9.62	Upgrade Freeway to Standards	Urban	5 ~ 20 Million	Moderate	None	Good
P30	D7	GC 4	25.36	Upgrade Nonfreeway To Standards	Rural	20~50 Million	Complex	None	Good
P31	D7	GC 16	5.56	Bridge Replacement/New Bridge	Urban	5 ~ 20 Million	Moderate	None	Average
P32	D7	GC 21	3.60	Widen Freeway	Urban	< 5 Million	Simple	None	Average
P33	D7	GC 5	1.35	Widen Nonfreeway	Urban	< 5 Million	Simple	None	Good
P34	D7	GC 15	12.26	New Location Freeway	Rural	5 ~ 20 Million	Moderate	None	Good
P35	D7	GC 9	20.16	New Location Freeway	Rural	20~50 Million	Moderate	None	Good

Appendix H. Production Rates Data for this Study

Excavation

DP ID	Project ID	Work Zone Accessibility	Work Zone Congestion	Work Zone Drainage	Work Zone Clay Content	Soil Condition	Work Area Quantity (CY)	Production Rate (CY/Crew Day)
110001	P12	Moderate	Moderate	Quickly Drained	High	Stiff	2601.00	1,300.50
110002	P13	Difficult	Moderate	Moderate	Moderate	Stiff	1200.00	600.00
110003	P16	Difficult	Severe	Easily Flooded	High	Stiff	970.00	242.50
110004	P8	Moderate	Minor	Moderate	Low	Rocky	1969.00	787.60
110005	P8	Moderate	Minor	Moderate	Low	Rocky	4004.00	2,002.00
110006	P7	Moderate	Moderate	Moderate	Moderate	Stiff	2472.00	618.00
110007	P7	Easy	Minor	Quickly Drained	Moderate	Stiff	10673.00	3,557.67
110008	P7	Moderate	Moderate	Quickly Drained	Moderate	Stiff	1071.00	535.50
110009	P7	Moderate	Severe	Moderate	Moderate	Stiff	16798.00	2,799.67
110010	P8	Easy	Moderate	Quickly Drained	Low	Rocky	2478.00	619.50
110011	P7	Moderate	Moderate	Moderate	Moderate	Stiff	7377.00	922.13
110012	P7	Moderate	Moderate	Quickly Drained	Moderate	Stiff	1766.00	883.00
110013	P7	Easy	Minor	Quickly Drained	Moderate	Stiff	668.00	267.20
110014	P8	Easy	Moderate	Quickly Drained	Low	Rocky	2198.00	628.00
110015	P8	Difficult	Moderate	Easily Flooded	Low	Rocky	1394.00	557.60
110016	P4	Easy	Moderate	Quickly Drained	High	Rocky	13924.00	2,784.80
110017	P12	Easy	Minor	Quickly Drained	High	Stiff	4302.00	860.40
110018	P11	Easy	Moderate	Quickly Drained	Moderate	Stiff	360.00	360.00
110019	P16	Easy	Minor	Quickly Drained	High	Stiff	1064.00	709.33
110020	P19	Difficult	Moderate	Moderate	High	Loose	4640.00	1,546.67
110021	P19	Difficult	Moderate	Moderate	High	Loose	2600.00	1,300.00
110022	P23	Moderate	Severe	Quickly Drained	Moderate	Stiff	1536.00	1,536.00
110023	P30	Easy	Minor	Quickly Drained	High	Stiff	4560.00	1,140.00
110024	P35	Easy	Minor	Quickly Drained	Low	Rocky	7353.00	1,935.00
110025	P30	Easy	Minor	Easily Flooded	High	Stiff	5237.00	1,540.29
110026	P33	Easy	Moderate	Quickly Drained	Moderate	Stiff	995.00	199.00

Appendix H. Production Rates Data for this Study (Cont'd)

Embankment

DP ID	Project ID	Work Zone Accessibility	Work Zone Congestion	Work Zone Drainage	Soil Condition	Work Area Quantity (CY)	Production Rate (CY/Crew Day)
132001	P12	Moderate	Moderate	Quickly Drained	Stiff	2601.00	325.13
132002	P13	Difficult	Moderate	Moderate	Stiff	1200.00	600.00
132003	P8	Moderate	Minor	Moderate	Rocky	1969.00	656.33
132004	P8	Moderate	Minor	Moderate	Rocky	4004.00	2002.00
132005	P7	Difficult	Moderate	Quickly Drained	Stiff	7377.00	819.67
132006	P7	Difficult	Moderate	Quickly Drained	Stiff	1071.00	535.50
132007	P8	Moderate	Minor	Moderate	Rocky	2478.00	619.50
132008	P8	Moderate	Moderate	Moderate	Rocky	2198.00	549.50
132009	P8	Difficult	Moderate	Quickly Drained	Rocky	1394.00	464.67
132010	P4	Moderate	Moderate	Quickly Drained	Rocky	10046.00	2009.20
132011	P4	Moderate	Moderate	Quickly Drained	Rocky	17838.00	849.43
132012	P10	Easy	Minor	Moderate	Loose	2693.00	448.83
132013	P9	Difficult	Severe	Quickly Drained	Stiff	1243.00	248.60
132014	P8	Easy	Moderate	Quickly Drained	Rocky	5728.00	1145.60
132015	P8	Moderate	Minor	Quickly Drained	Rocky	7920.00	1584.00
132016	P8	Moderate	Moderate	Moderate	Rocky	2051.00	683.67
132017	P8	Easy	Minor	Moderate	Rocky	12936.00	2156.00
132018	P8	Moderate	Minor	Quickly Drained	Rocky	6632.00	1326.40
132019	P7	Difficult	Moderate	Quickly Drained	Stiff	1766.00	588.67
132020	P16	Easy	Moderate	Quickly Drained	Stiff	1064.00	709.33
132021	P19	Difficult	Moderate	Moderate	Loose	4640.00	1546.67
132022	P19	Difficult	Moderate	Moderate	Loose	2600.00	1300.00
132023	P23	Moderate	Minor	Quickly Drained	Stiff	1536.00	1536.00
132024	P23	Moderate	Minor	Quickly Drained	Stiff	1536.00	1536.00
132025	P25	Moderate	Minor	Moderate	Loose	3000.00	3000.00
132026	P24	Moderate	Minor	Quickly Drained	Stiff	18753.00	1442.54
132027	P24	Moderate	Minor	Quickly Drained	Stiff	6447.00	805.88
132028	P25	Moderate	Moderate	Easily Flooded	Loose	1500.00	750.00
132029	P24	Moderate	Moderate	Quickly Drained	Stiff	9261.00	1157.63
132030	P18	Moderate	Moderate	Quickly Drained	Loose	28880.00	1375.24
132031	P30	Easy	Minor	Quickly Drained	Stiff	4280.00	1070.00
132032	P35	Easy	Minor	Quickly Drained	Rocky	33938.00	1786.21
132033	P30	Easy	Minor	Easily Flooded	Stiff	23674.00	1392.59
132034	P33	Easy	Moderate	Quickly Drained	Stiff	3161.00	287.36

Appendix H. Production Rates Data for this Study (Cont'd)

Lime-Treated Sub-grade

DP ID	Project ID	Work Zone Congestion	Work Zone Clay Content	Work Zone Land Slope	Soil Condition	Work Area Quantity (SY)	Length of Work Area (LF)	Width of Work Area (LF)	Thickness	Type C hydraulic Lime Application	Production Rate (SY/Crew Day)
260001	P12	Moderate	High	Flat	Stiff	23,010	6,472	32	6"	No	2,557
260002	P14	Severe	High	Flat	Rocky	1,632	708	21	6"	No	233
260003	P16	Severe	High	Moderate	Stiff	409	200	18	6"	No	82
260004	P7	Moderate	Moderate	Flat	Stiff	3,291	456	53	6"	No	658
260005	P7	Moderate	Moderate	Flat	Stiff	5,180	304	53	6"	No	740
260006	P12	Moderate	High	Flat	Stiff	18,449	5,301	31	6"	No	1,677
260007	P5	Minor	Moderate	Flat	Stiff	3,701	558	60	6"	No	1,234
260008	P5	Minor	Moderate	Flat	Stiff	3,730	974	34	6"	No	933
260009	P6	Moderate	Moderate	Flat	Loose	11,026	3,135	32	6"	No	1,838
260010	P5	Moderate	Moderate	Moderate	Stiff	9,361	1,758	48	6"	No	1,872
260011	P24	Moderate	High	Flat	Stiff	31,019	6,647	42	6"	No	3,102
260012	P24	Moderate	High	Flat	Stiff	11,165	3,588	31	6"	No	3,722
260013	P1	Moderate	Moderate	Flat	Loose	7,041	1,647	38	6"	Yes	1,760
260014	P1	Minor	Moderate	Flat	Loose	10,458	2,445	38	6"	Yes	747
260015	P1	Minor	Moderate	Flat	Loose	5,553	990	50	6"	Yes	1,111
260016	P19	Moderate	High	Flat	Loose	50,490	9,621	47	6"	No	3,156
260017	P20	Minor	High	Flat	Loose	17,007	4,449	34	6"	No	2,430
260018	P18	Minor	High	Flat	Loose	5,758	1,151	45	6"	No	1,440
260019	P22	Minor	High	Flat	Loose	5,583	450	111	6"	Yes	1,117
260020	P18	Minor	High	Flat	Loose	7,239	1,303	50	6"	No	1,207
260021	P18	Minor	High	Flat	Loose	10,167	1,830	50	6"	No	1,695
260022	P21	Minor	High	Steep	Loose	6,848	1,284	48	6"	Yes	856
260023	P18	Moderate	High	Flat	Loose	5,490	1,247	40	6"	No	1,098
260024	P19	Moderate	High	Flat	Loose	13,104	2,106	56	6"	No	1,638
260025	P19	Moderate	High	Flat	Loose	13,601	2,106	56	6"	No	1,700
260026	P6	Moderate	Moderate	Flat	Loose	26,645	6,002	45	6"	No	2,961
260027	P5	Moderate	Moderate	Moderate	Stiff	18,463	4,226	39	6"	Yes	3,077
260028	P25	Moderate	Moderate	Flat	Loose	3,033	900	30	6"	No	758
260029	P29	Minor	High	Flat	Stiff	7,275	1,169	56	6"	Yes	1,119
260030	P32	Minor	High	Flat	Stiff	15,569	3,357	42	6"	Yes	865
260031	P33	Moderate	Moderate	Moderate	Stiff	7,380	3,087	22	6"	Yes	1,230
260032	P30	Minor	High	Flat	Stiff	12,558	2,512	45	6"	Yes	1,395

Appendix H. Production Rates Data for this Study (Cont'd)

Aggregate Base Course

DP ID	Project ID	Type of Base Material	Work Zone Congestion	Work Zone Land Slope	Soil Condition	Work Area Quantity (SY-Lift)	Lift-Length of Work Area (LF)	Width of Work Area (LF)	Lift-Height (Inch)	Production Rate (SY-Lift/Crew Day)
247001	P25	Cement Treated Base	Moderate	Flat	Loose	3087.00	947.00	29.00	6.00	3087.00
247002	P21	Cement Treated Base	Minor	Steep	Loose	6601.00	1324.00	46.00	6.00	2200.33
247003	P18	Cement Treated Base	Minor	Flat	Loose	1416.00	250.00	51.00	6.00	1416.00
247004	P19	Cement Treated Base	Moderate	Flat	Loose	16250.00	2125.00	68.00	6.00	6500.00
247005	P19	Cement Treated Base	Moderate	Flat	Loose	8211.00	1275.00	58.00	6.00	4105.50
247006	P18	Cement Treated Base	Moderate	Moderate	Loose	6824.00	770.00	75.00	6.00	3412.00
247007	P18	Cement Treated Base	Moderate	Flat	Loose	6431.00	2217.00	27.00	6.00	3215.50
247008	P18	Cement Treated Base	Minor	Flat	Loose	7827.00	1409.00	50.00	6.00	3913.50
247009	P20	Cement Treated Base	Minor	Flat	Loose	3916.00	1137.00	31.00	6.00	3916.00
247010	P18	Cement Treated Base	Minor	Steep	Loose	4408.00	694.00	57.00	6.00	4408.00
247011	P24	Cement Treated Base	Moderate	Flat	Stiff	7319.00	2114.00	31.00	6.00	4879.33
247012	P19	Cement Treated Base	Moderate	Flat	Loose	35956.00	6995.00	46.00	6.00	5992.67
247013	P24	Cement Treated Base	Moderate	Flat	Stiff	31266.00	3250.00	42.00	6.00	5211.00
247014	P20	Cement Treated Base	Minor	Flat	Loose	17796.00	4449.00	36.00	6.00	4449.00

DP ID	Project ID	Type of Base Material	Work Zone Congestion	Work Zone Land Slope	Soil Condition	Work Area Quantity (SY-Lift)	Lift-Length of Work Area (LF)	Width of Work Area (LF)	Lift-Height (Inch)	Production Rate (SY-Lift/Crew Day)
247101	P13	Flexible Base	Minor	Moderate	Stiff	1579.00	263.00	54.00	8.00	526.33
247102	P15	Flexible Base	Minor	Moderate	Stiff	9556.00	1476.00	58.00	3.00	3185.33
247103	P4	Flexible Base	Moderate	Flat	Rocky	41607.00	11371.00	33.00	5.50	2971.93
247104	P5	Flexible Base	Moderate	Moderate	Stiff	10020.00	2060.00	43.00	4.50	2505.00
247105	P6	Flexible Base	Moderate	Flat	Loose	29011.00	6150.00	42.50	6.50	4144.43
247106	P5	Flexible Base	Moderate	Moderate	Stiff	26693.00	5950.00	40.00	4.50	2965.89
247107	P6	Flexible Base	Moderate	Flat	Loose	39628.00	8492.00	42.00	4.50	4953.50
247108	P5	Flexible Base	Minor	Flat	Stiff	28776.00	7510.00	34.50	4.50	3597.00
247109	P5	Flexible Base	Minor	Flat	Stiff	6283.00	2520.00	37.50	4.50	2094.33
247110	P7	Flexible Base	Moderate	Flat	Stiff	6773.00	850.00	72.00	6.00	967.57
247111	P10	Flexible Base	Minor	Flat	Loose	7612.00	1054.00	65.00	6.00	1087.43
247112	P6	Flexible Base	Minor	Flat	Loose	2491.00	520.00	43.00	6.50	1245.50
247113	P34	Flexible Base	Minor	Moderate	Rocky	5556.00	2000.00	25.00	9.00	2778.00
247114	P30	Flexible Base	Minor	Flat	Stiff	19685.00	2952.00	60.00	6.00	5624.29
247115	P30	Flexible Base	Minor	Flat	Stiff	22248.00	4450.00	45.00	6.00	3178.29

Appendix H. Production Rates Data for this Study (Cont'd)

Hot Mix Asphalt Pavement

DP ID	Project ID	Work Zone Accessibility	Work Zone Congestion	Work Zone Land Slope	Work Area Quantity (Ton)	Course Type	Main Lane Application	Production Rate (Ton/Crew Day)
340001	P12	Easy	Moderate	Flat	5840.00	Base Course	Yes	1460.00
340002	P13	Easy	Minor	Flat	4500.00	Base Course	Yes	750.00
340003	P1	Easy	Minor	Flat	2372.00	Base Course	Yes	1186.00
340004	P7	Easy	Minor	Flat	3011.00	Base Course	Yes	602.20
340005	P2	Easy	Severe	Moderate	397.00	Surface	No	397.00
340006	P4	Easy	Moderate	Flat	694.00	Surface	Yes	347.00
340007	P4	Easy	Severe	Flat	1139.00	Surface	Yes	379.67
340008	P4	Easy	Moderate	Flat	2964.00	Surface	Yes	988.00
340009	P3	Easy	Minor	Steep	963.00	Base Course	No	963.00
340010	P8	Easy	Moderate	Flat	1182.00	Base Course	No	1182.00
340011	P7	Easy	Moderate	Flat	2723.00	Surface and Base	No	907.67
340012	P12	Easy	Moderate	Flat	2788.00	Base Course	Yes	1394.00
340013	P16	Easy	Severe	Flat	783.00	Base Course	No	783.00
340014	P20	Easy	Moderate	Flat	964.00	Base Course	Yes	642.67
340015	P20	Easy	Moderate	Flat	942.00	Base Course	Yes	628.00
340016	P19	Easy	Minor	Flat	1318.00	Base Course	Yes	659.00
340017	P19	Easy	Moderate	Flat	482.00	Base Course	Yes	482.00
340018	P26	Moderate	Moderate	Flat	614.00	Surface	Yes	307.00
340019	P25	Moderate	Severe	Flat	316.00	Surface	Yes	158.00
340020	P26	Moderate	Moderate	Flat	1062.00	Base Course	No	531.00
340021	P24	Easy	Moderate	Flat	975.00	Base Course	Yes	975.00
340022	P27	Easy	Minor	Flat	3010.00	Base Course	No	1204.00
340023	P27	Moderate	Severe	Flat	2115.00	Base Course	No	1410.00
340024	P28	Easy	Minor	Flat	2800.00	Surface	Yes	1400.00
340025	P27	Easy	Minor	Flat	1519.15	Base Course	No	759.58
340026	P31	Moderate	Moderate	Flat	2996.00	Surface	Yes	749.00
340027	P32	Easy	Minor	Flat	1588.00	Base Course	No	794.00
340028	P31	Moderate	Moderate	Flat	3268.06	Surface	Yes	1089.35
340029	P32	Moderate	Moderate	Flat	940.00	Base Course	No	940.00
340030	P32	Easy	Moderate	Flat	5828.00	Base Course	Yes	777.07
340031	P32	Easy	Minor	Flat	832.00	Base Course	Yes	832.00
340032	P34	Easy	Minor	Moderate	227.00	Base Course	No	454.00

Appendix H. Production Rates Data for this Study (Cont'd)

Slip-form Concrete Pavement

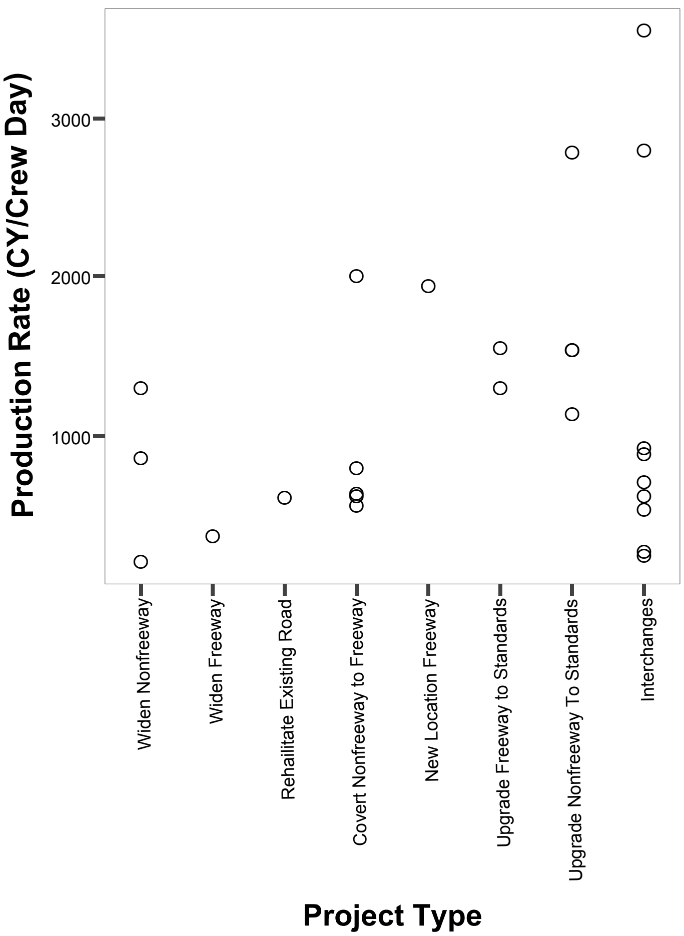
DP ID	Project ID	Type of Concrete Pavment	Work Zone Accessibility	Work Zone Congestion	Work Zone Land Slope	Work Area Quantity (SY)	Length of Work Area (LF)	Width of Work Area (LF)	Lift-Thickness (Inch)	Production Rate (SY/Crew Day)
360101	P18	CRCP	Moderate	Moderate	Flat	8940.00	4013.00	20.00	10	1625.45
360102	P18	CRCP	Moderate	Moderate	Flat	10768.00	4038.00	24.00	10	2153.60
360103	P14	JCP	Difficult	Severe	Flat	4088.00	1533.00	24.00	13	2044.00
360104	P13	CRCP	Easy	Minor	Flat	740.00	303.00	22.00	13	740.00
360105	P14	JCP	Moderate	Severe	Flat	2152.00	1614.00	12.00	8	2152.00
360106	P12	CRCP	Easy	Moderate	Flat	5153.00	3303.00	14.00	8	1288.25
360107	P17	CRCP	Easy	Minor	Flat	38896.00	15912.00	22.00	13	1994.67
360108	P16	CRCP	Difficult	Moderate	Moderate	1600.00	600.00	24.00	13	800.00
360109	P12	CRCP	Easy	Moderate	Flat	6746.00	3795.00	14.00	8	1124.33
360110	P13	CRCP	Easy	Moderate	Moderate	1156.00	473.00	22.00	13	462.40
360111	P14	JCP	Moderate	Severe	Flat	1984.00	1446.00	12.00	13	992.00
360112	P17	CRCP	Easy	Minor	Flat	3321.00	1624.00	22.00	13	1328.40
360113	P19	CRCP	Moderate	Moderate	Flat	4889.00	2000.00	22.00	10	977.80
360114	P19	CRCP	Moderate	Moderate	Flat	9873.00	4040.00	22.00	10	1410.43
360115	P20	CRCP	Easy	Moderate	Flat	7456.00	3050.00	22.00	10	1242.67
360116	P20	CRCP	Easy	Moderate	Flat	9820.00	7615.00	12.00	10	1227.50
360117	P20	CRCP	Easy	Minor	Flat	2000.00	1500.00	12.00	10	1000.00
360118	P20	CRCP	Moderate	Minor	Flat	4119.00	1685.00	22.00	10	1373.00
360119	P24	CRCP	Easy	Severe	Flat	18592.00	7783.00	22.00	13	1690.18
360120	P24	CRCP	Easy	Moderate	Flat	9754.00	4083.00	22.00	13	1625.67
360121	P27	CRCP	Moderate	Severe	Flat	4953.00	3547.00	14.00	8	707.57
360122	P27	CRCP	Moderate	Moderate	Flat	3996.00	4045.00	12.00	8	999.00
360123	P27	CRCP	Easy	Minor	Flat	8361.00	6270.00	12.00	8	1286.31

Appendix H. Production Rates Data for this Study (Cont'd)

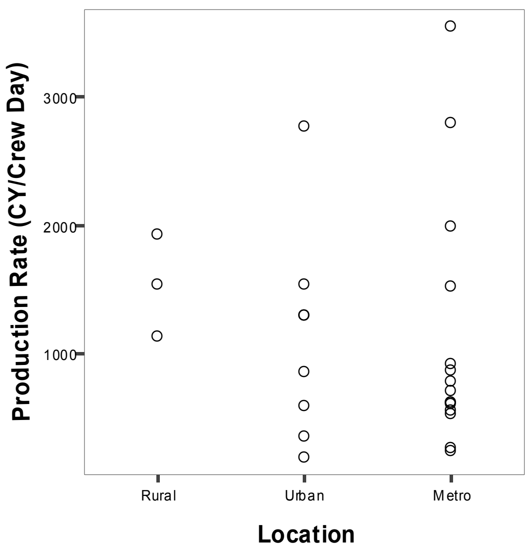
Conventional Form Concrete Pavement

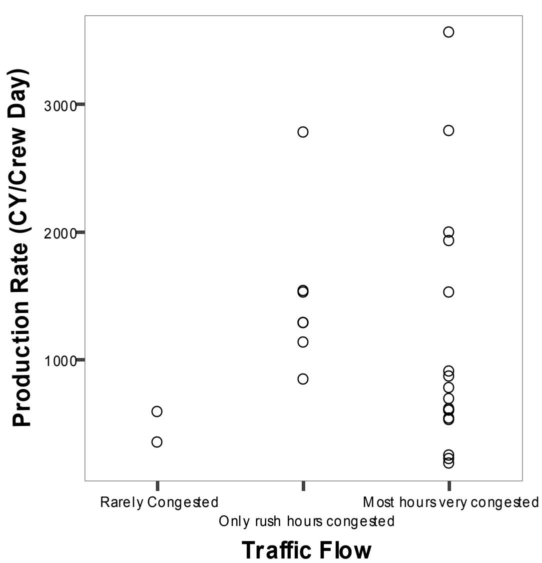
DP ID	Project ID	Work Zone Accessibility	Work Zone Congestion	Work Zone Land Slope	Work Area Quantity (SY)	Configuration	Thickness(in)	Production Rate (SY/Crew Day)
360201	P14	Difficult	Severe	Flat	766.00	Typical	13.00	383.00
360202	P14	Difficult	Severe	Flat	919.00	Typical	8.00	459.50
360203	P20	Easy	Moderate	Flat	1002.00	Non-typical	9.00	250.50
360204	P26	Moderate	Moderate	Flat	2621.00	Typical	10.00	582.44
360205	P19	Easy	Moderate	Flat	805.00	Typical	13.00	536.67
360206	P19	Moderate	Moderate	Flat	736.00	Typical	13.00	490.67
360207	P20	Easy	Moderate	Flat	4320.00	Typical	9.00	540.00
360208	P19	Easy	Moderate	Flat	614.00	Non-typical	6.00	307.00
360209	P19	Easy	Moderate	Flat	3265.00	Typical	10.00	362.78
360210	P20	Easy	Moderate	Flat	1560.00	Typical	9.00	390.00
360211	P20	Easy	Minor	Flat	581.00	Typical	9.00	290.50
360212	P18	Easy	Minor	Flat	423.00	Non-typical	10.00	211.50
360213	P13	Easy	Moderate	Flat	47.00	Non-typical	8.00	94.00
360214	P13	Easy	Minor	Flat	15.00	Non-typical	8.00	30.00
360215	P27	Moderate	Severe	Flat	914.00	Non-typical	8.00	228.50
360216	P27	Moderate	Severe	Flat	1364.00	Non-typical	8.00	341.00
360217	P27	Easy	Moderate	Flat	992.00	Non-typical	8.00	248.00
360218	P32	Easy	Minor	Moderate	405	Non-typical	8.00	135
360219	P32	Easy	Minor	Moderate	329	Non-typical	8.00	164.5
360220	P32	Easy	Minor	Moderate	211	Non-typical	8.00	70.33

Appendix I-1. Excavation: Scatter Plots of Observed Production Rates vs. Candidate Drivers

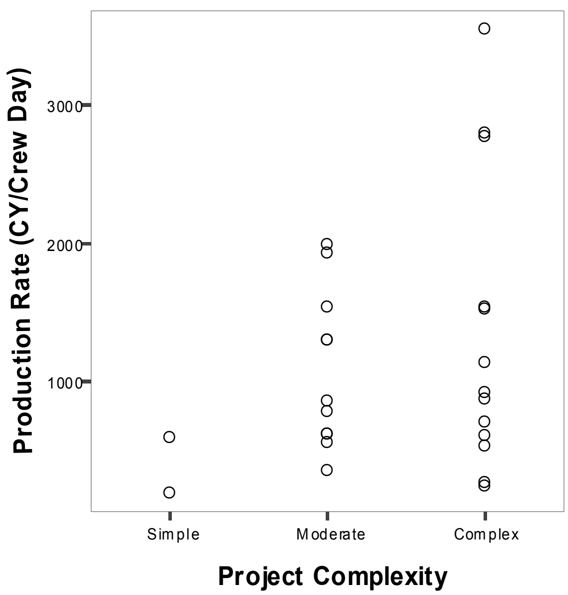


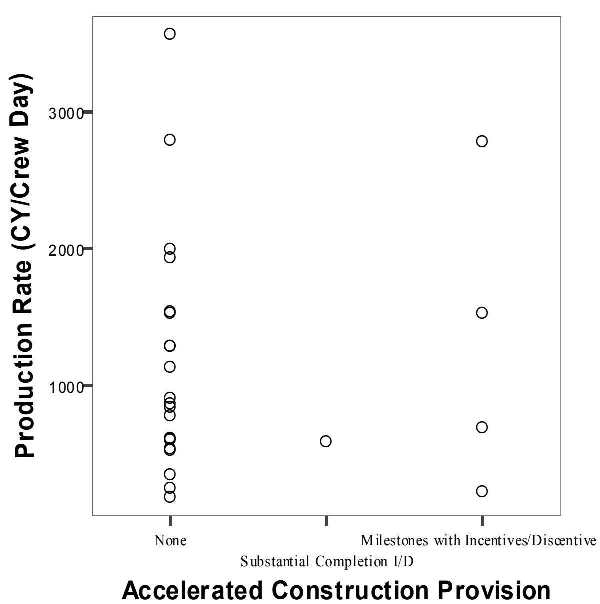
Appendix I-1. Excavation: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)



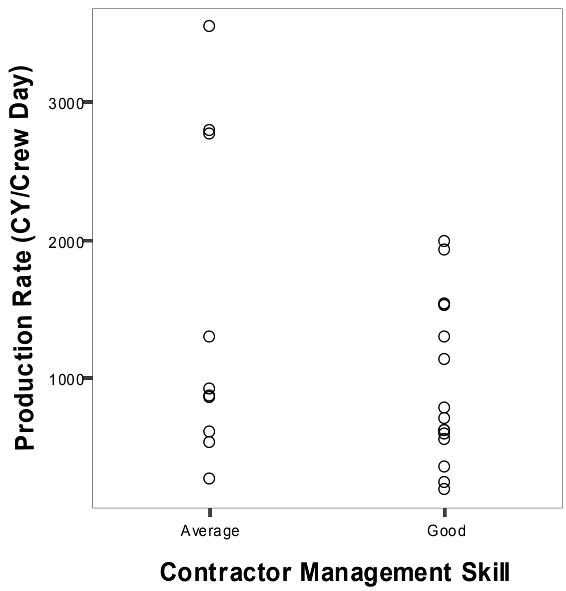


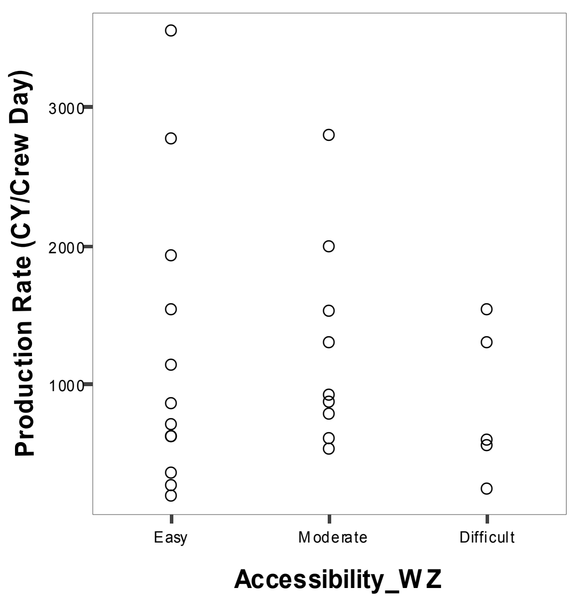
Appendix I-1. Excavation: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)



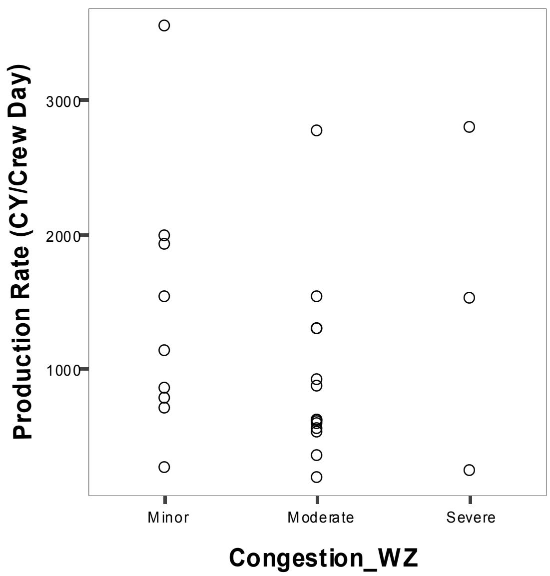


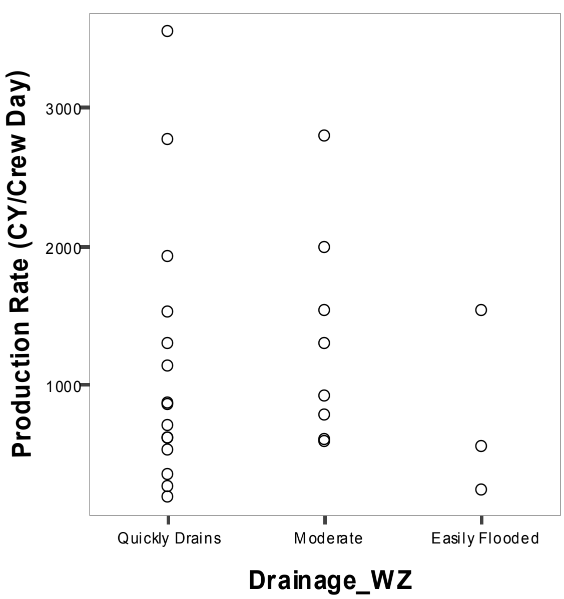
Appendix I-1. Excavation: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)



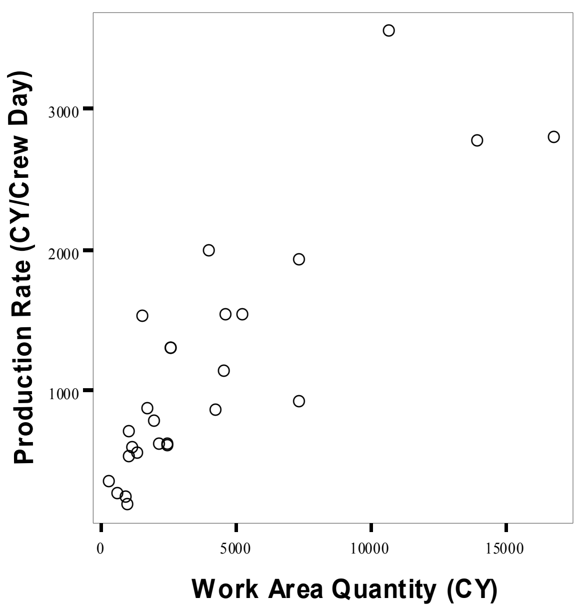


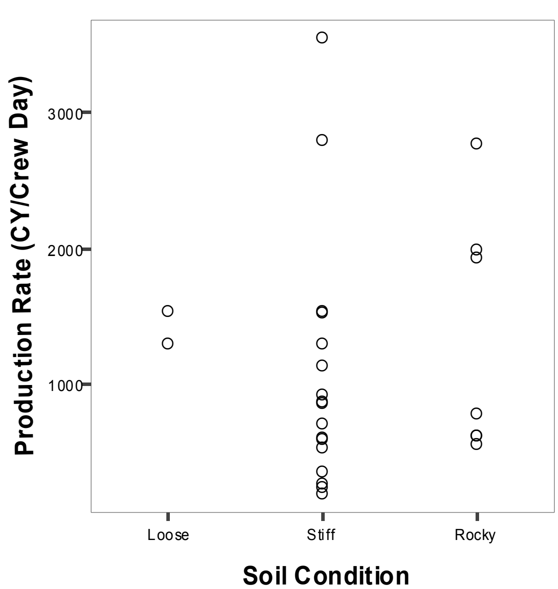
Appendix I-1. Excavation: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)



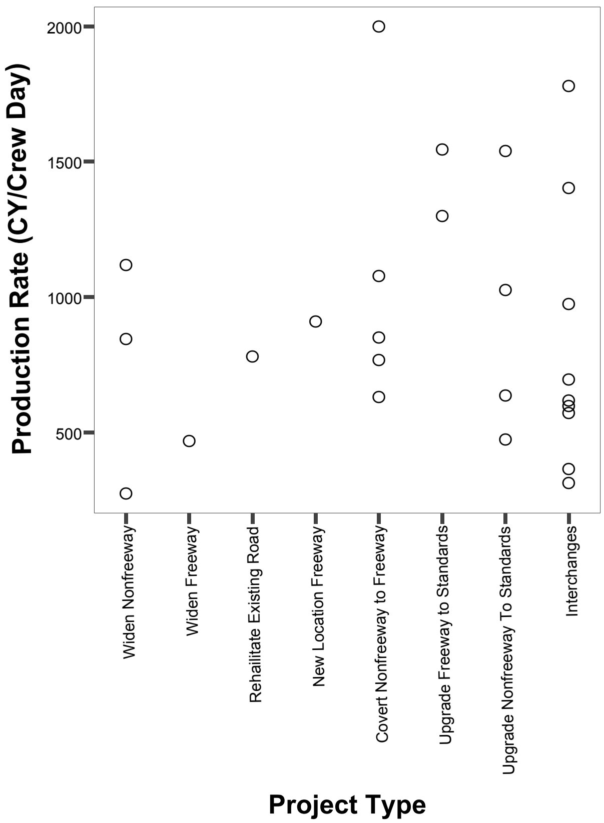


Appendix I-1. Excavation: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)

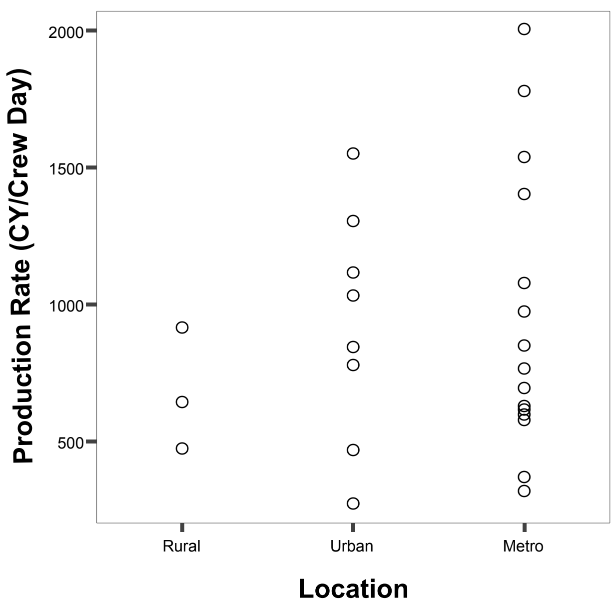


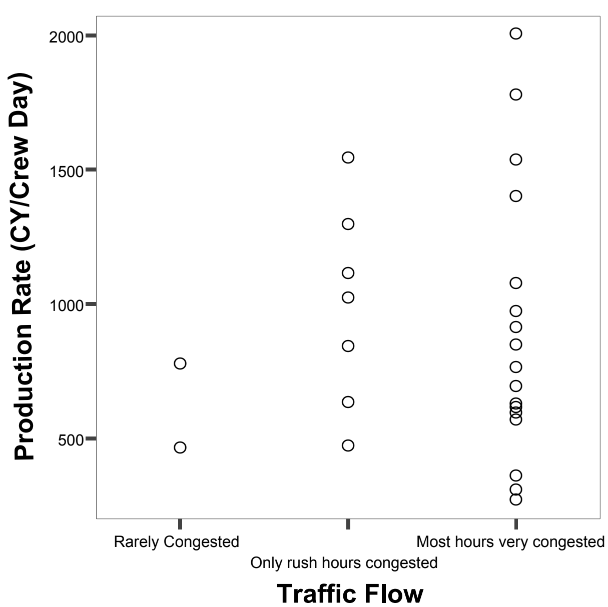


Appendix I-2. Excavation: Scatter Plots of Observed Production Rates (adjusted by crew size) vs. Candidate Drivers

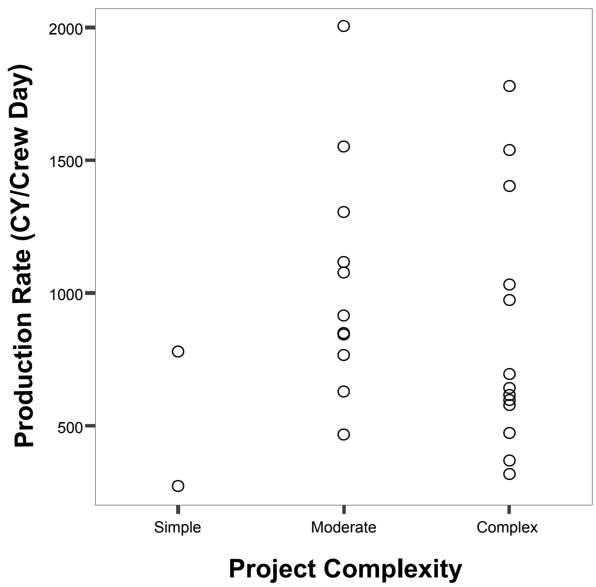


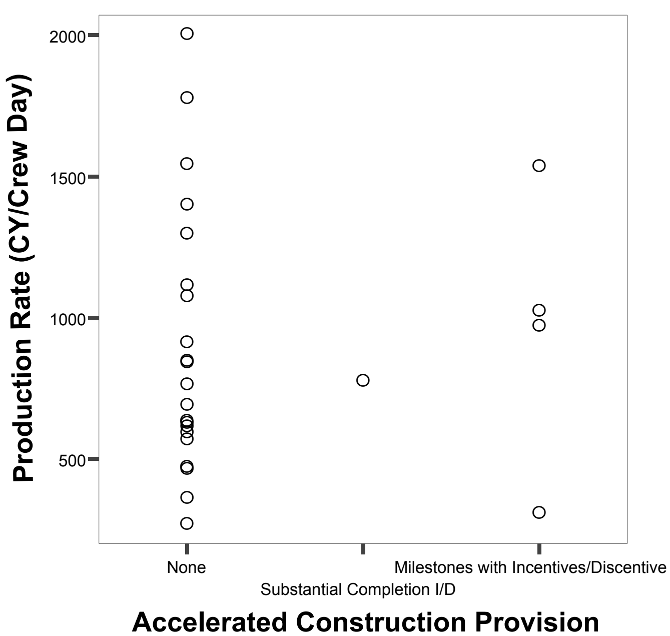
Appendix I-2. Excavation: Scatter Plots of Observed Production Rates (adjusted by crew size) vs. Candidate Drivers (Cont'd)



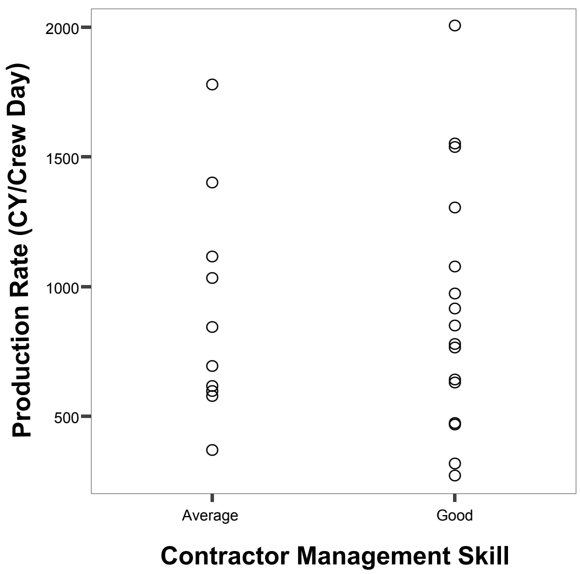


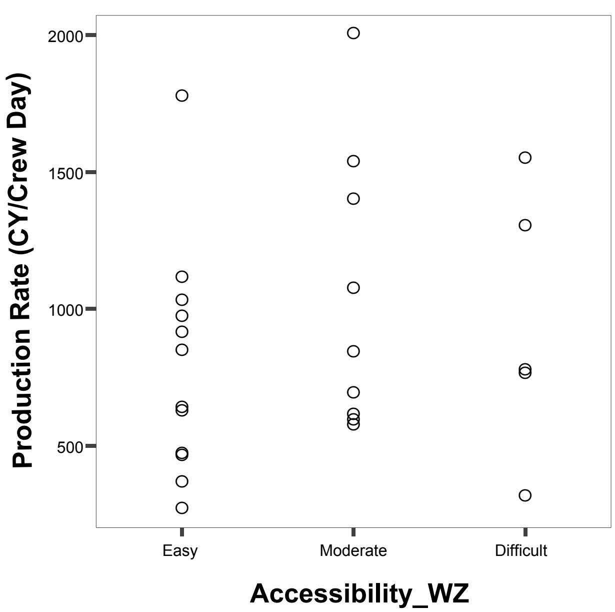
Appendix I-2. Excavation: Scatter Plots of Observed Production Rates (adjusted by crew size) vs. Candidate Drivers (Cont'd)



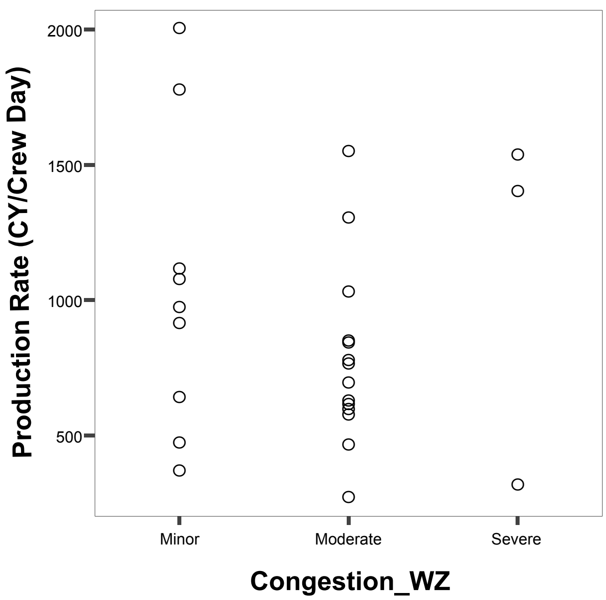


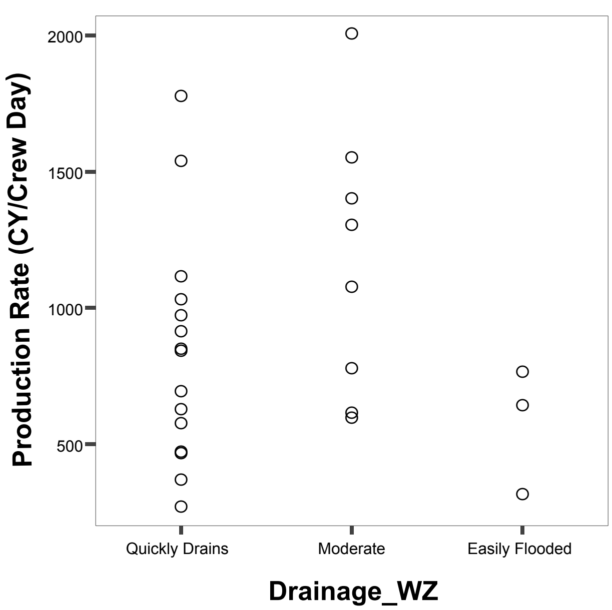
Appendix I-2. Excavation: Scatter Plots of Observed Production Rates (adjusted by crew size) vs. Candidate Drivers (Cont'd)



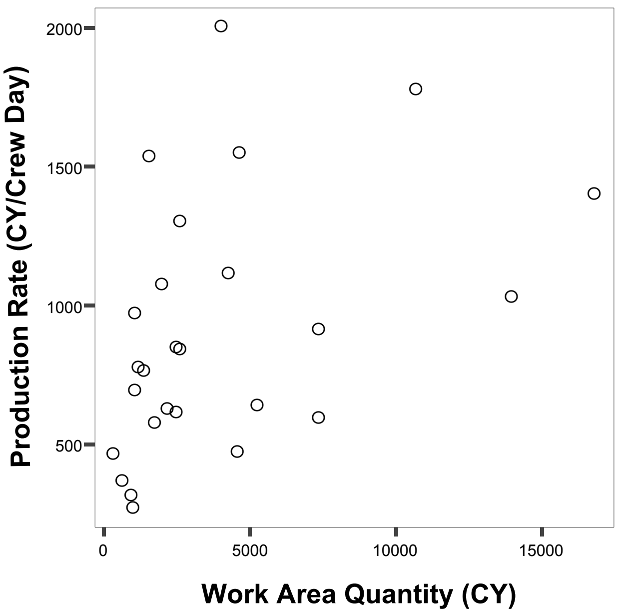


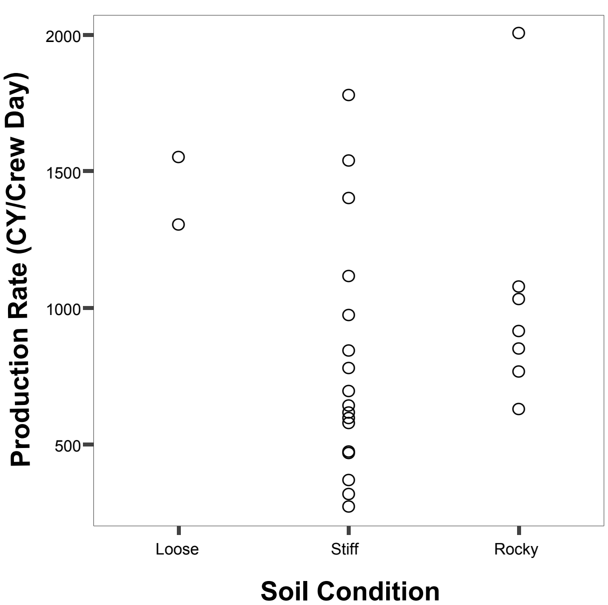
Appendix I-2. Excavation: Scatter Plots of Observed Production Rates (adjusted by crew size) vs. Candidate Drivers (Cont'd)



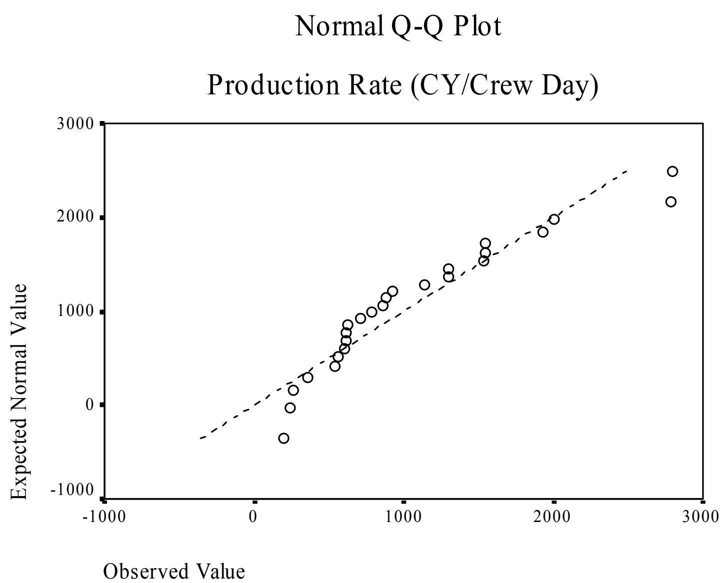


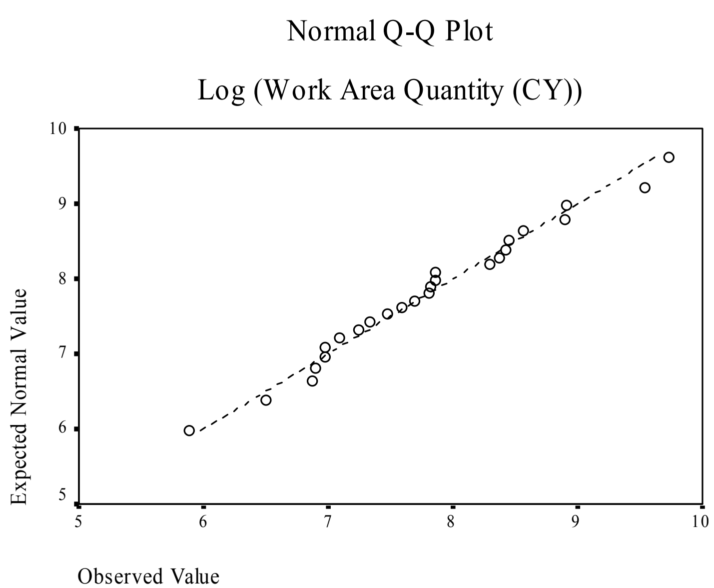
Appendix I-2. Excavation: Scatter Plots of Observed Production Rates (adjusted by crew size) vs. Candidate Drivers (Cont'd)



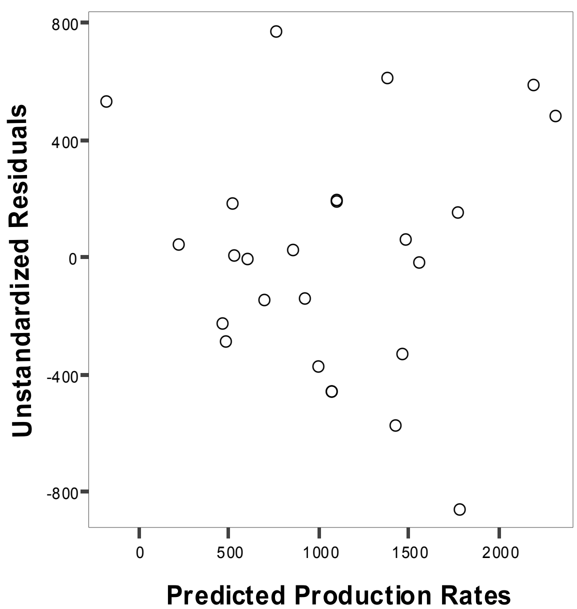


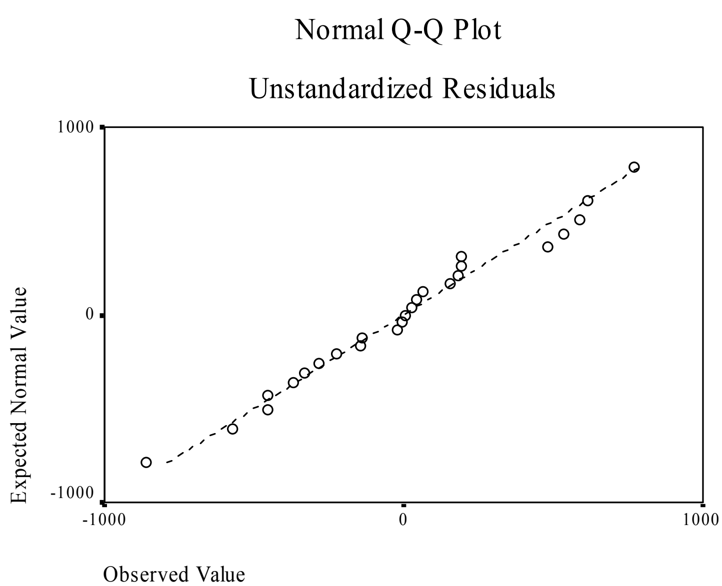
Appendix J. Results of Testing Assumptions of the Regression Analysis for Excavation: Production Rates vs. Work Area Quantity



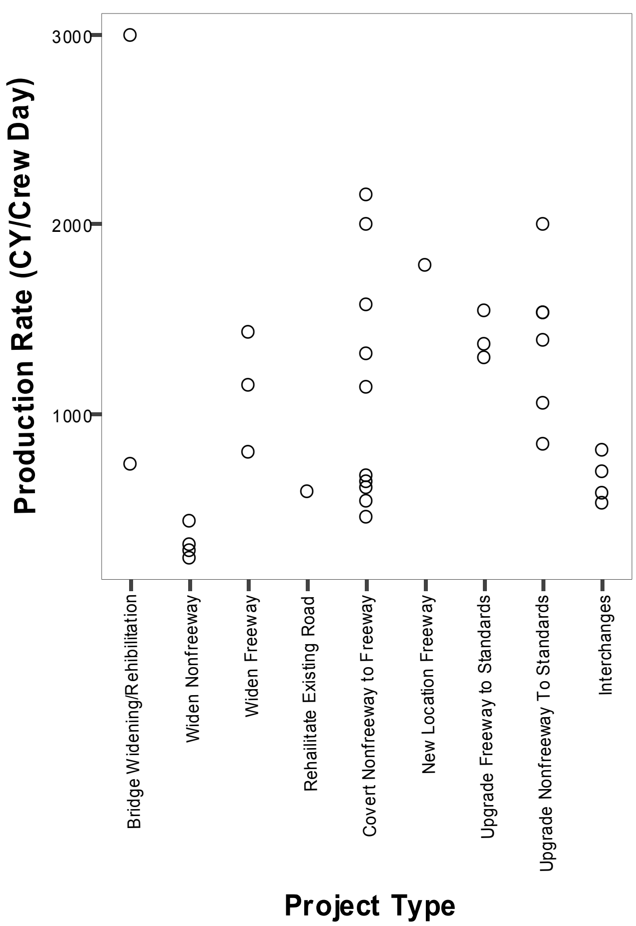


Appendix J. Results of Testing Assumptions of the Regression Analysis for Excavation: Production Rates vs. Work Area Quantity (Cont'd)

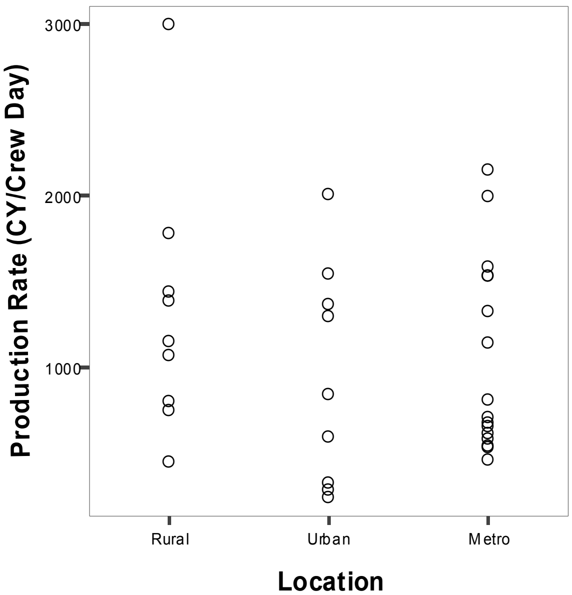


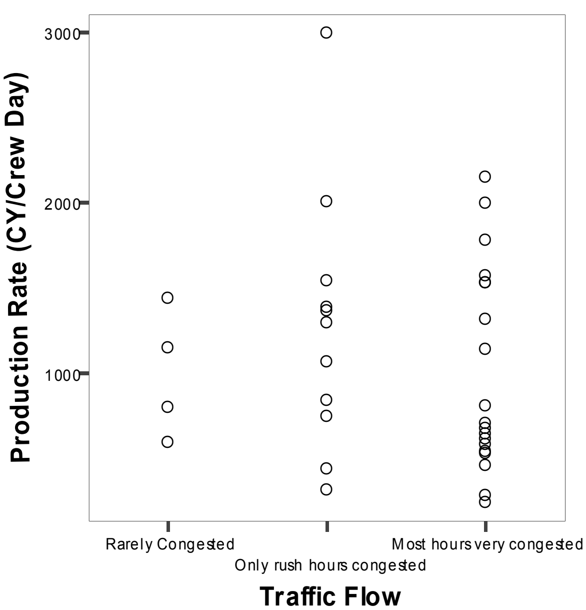


Appendix K. Embankment: Scatter Plots of Observed Production Rates vs. Candidate Drivers

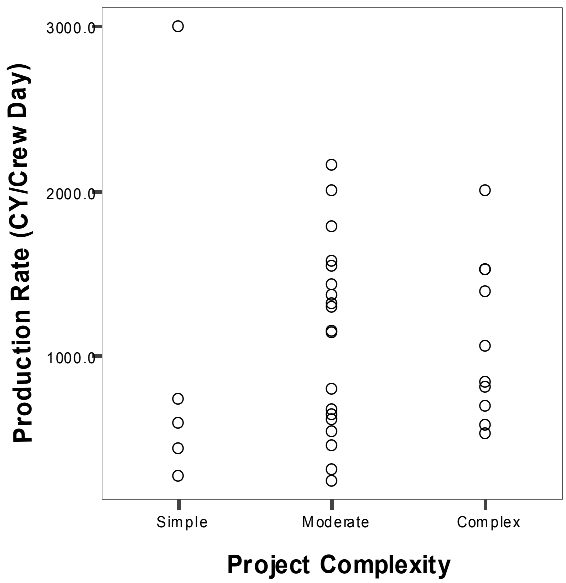


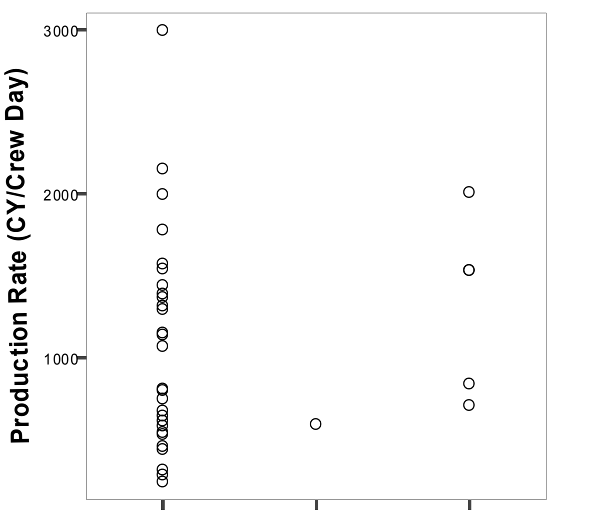
Appendix K. Embankment: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)



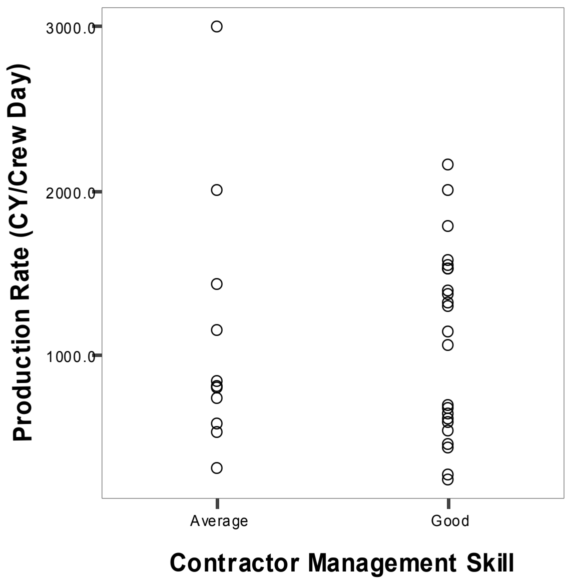


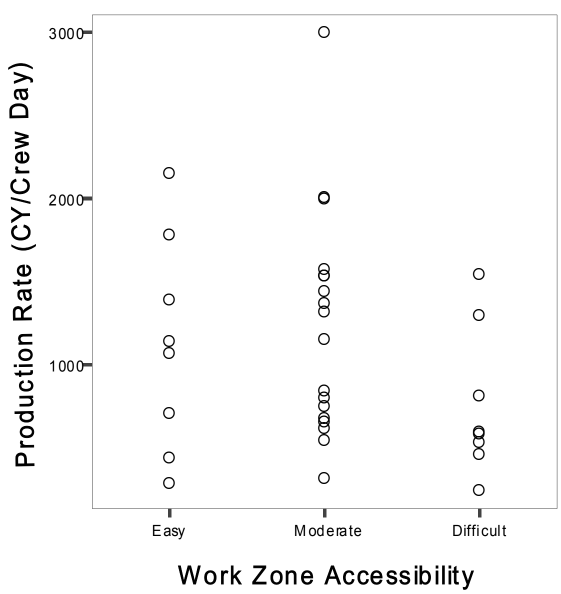
Appendix K. Embankment: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)



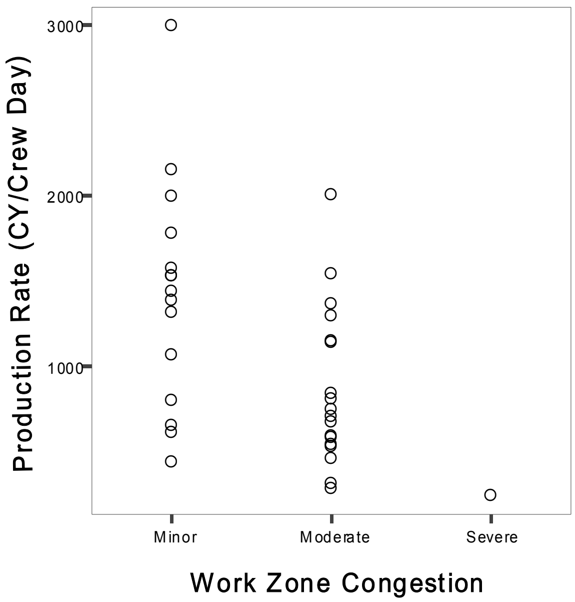


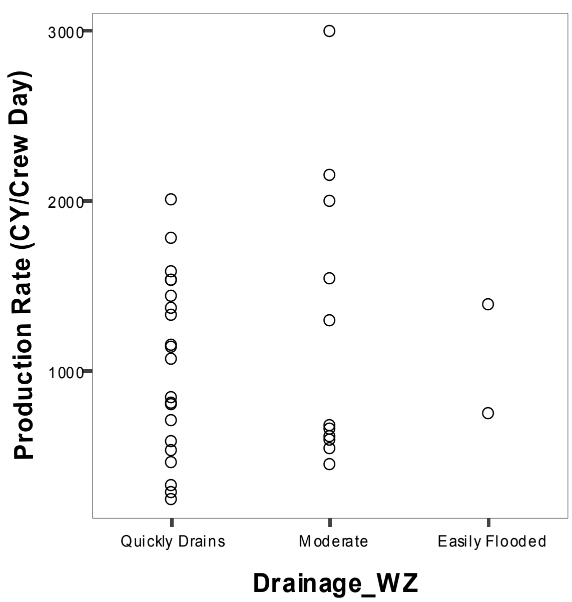
Appendix K. Embankment: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)



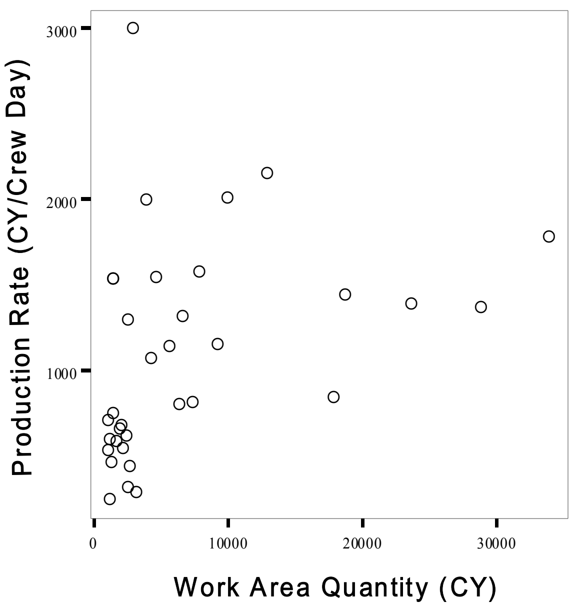


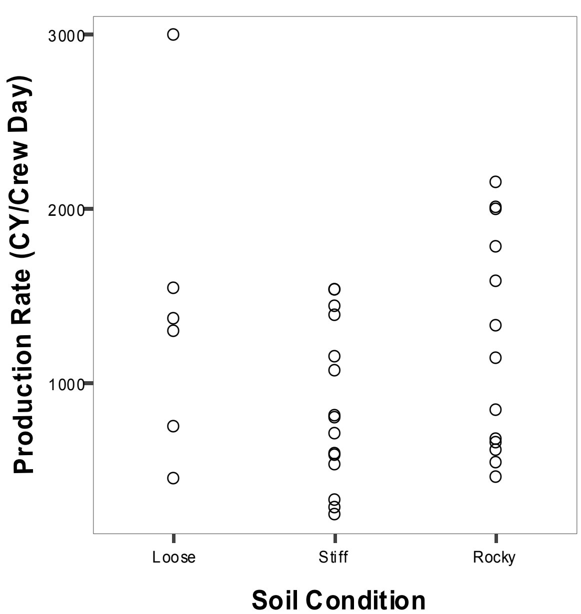
Appendix K. Embankment: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)





Appendix K. Embankment: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)

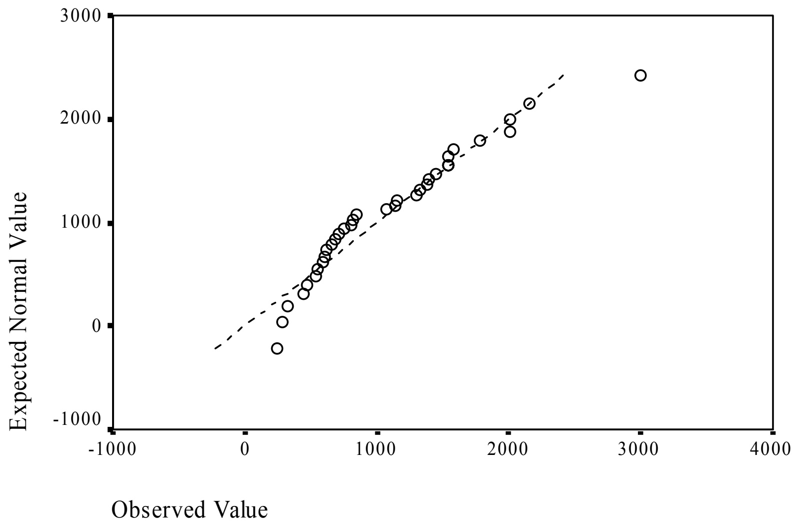




Appendix L-1. Results of Testing Assumptions of the Regression Analysis for Embankment: Production Rates and Work Area Quantity

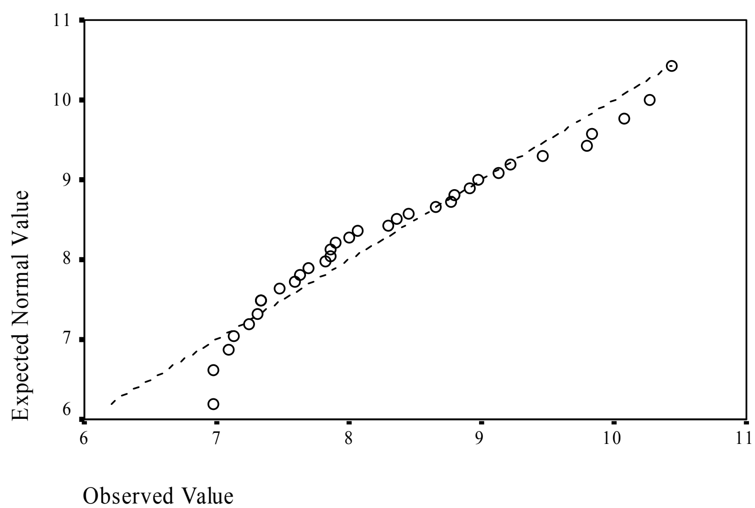
Normal Q-Q Plot

Production Rate (CY/Crew Day)

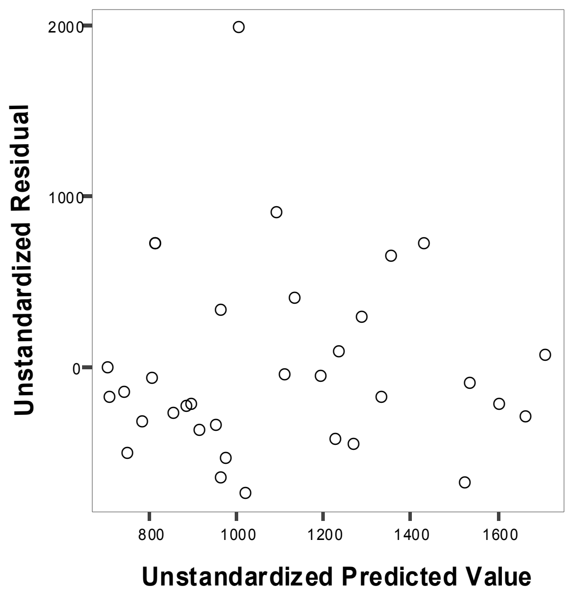


Normal Q-Q Plot

LOG (Work Area Quantity)

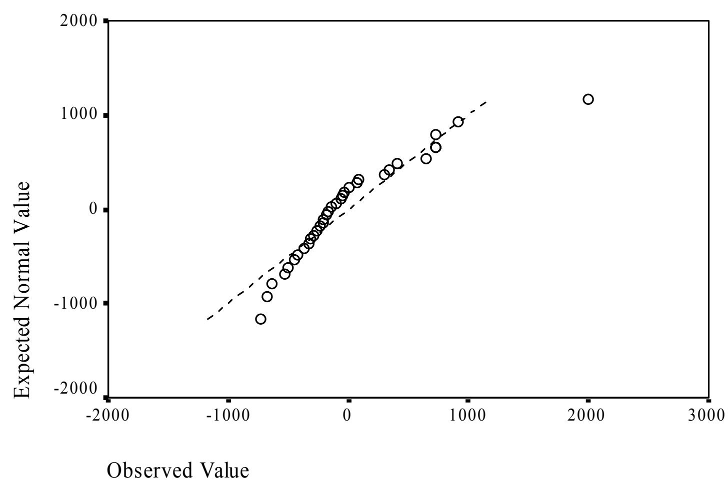


Appendix L-1. Results of Testing Assumptions of the Regression Analysis for Embankment: Production Rates and Work Area Quantity (Cont'd)



Normal Q-Q Plot

Unstandardized Residual

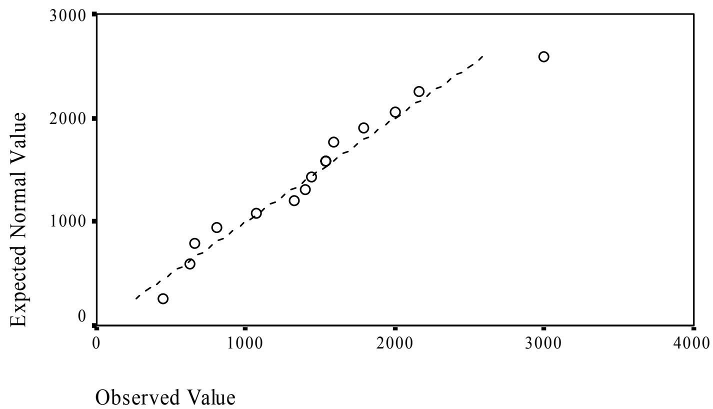


Appendix L-2. Results of Testing Normality of Variables for Embankment: Production Rates by Work Zone Congestion

Normal Q-Q Plot

Production Rate (CY/Crew Day)

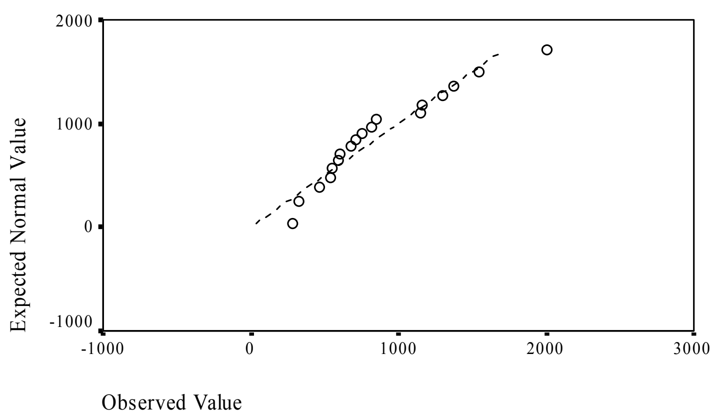
Minor Congestion



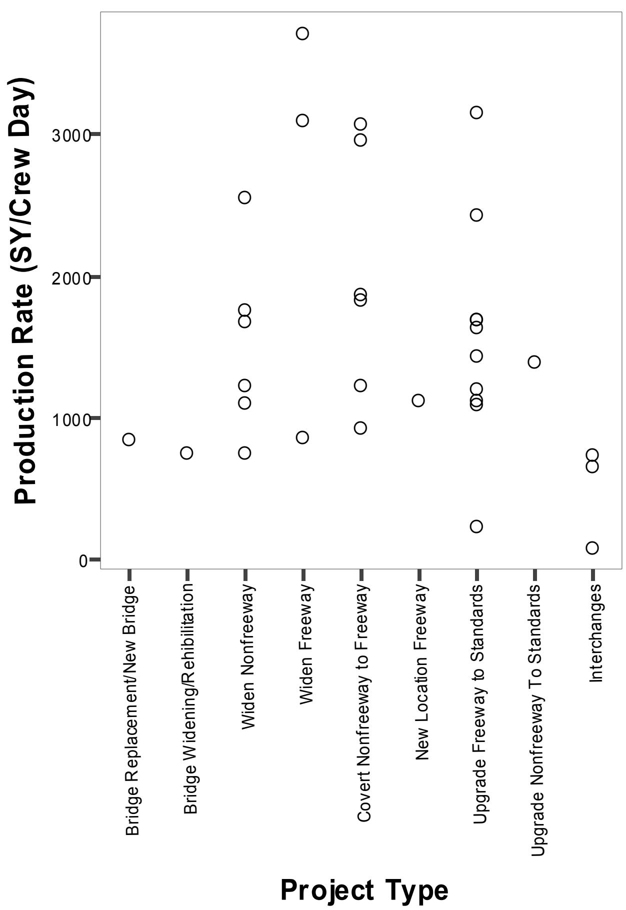
Normal Q-Q Plot

Production Rate (CY/Crew Day)

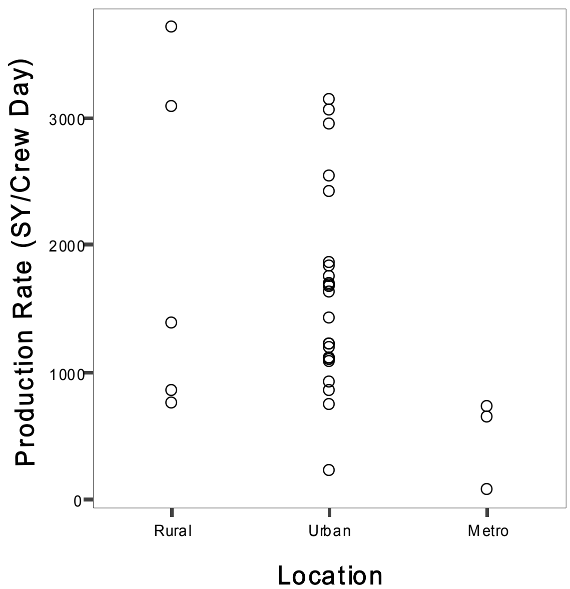
Moderate Congestion

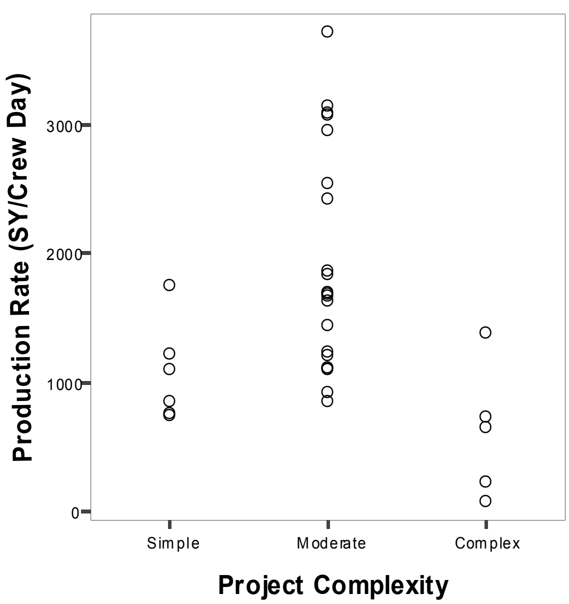


Appendix M. Lime-Treated Sub-grade: Scatter Plots of Observed Production Rates vs. Candidate Drivers

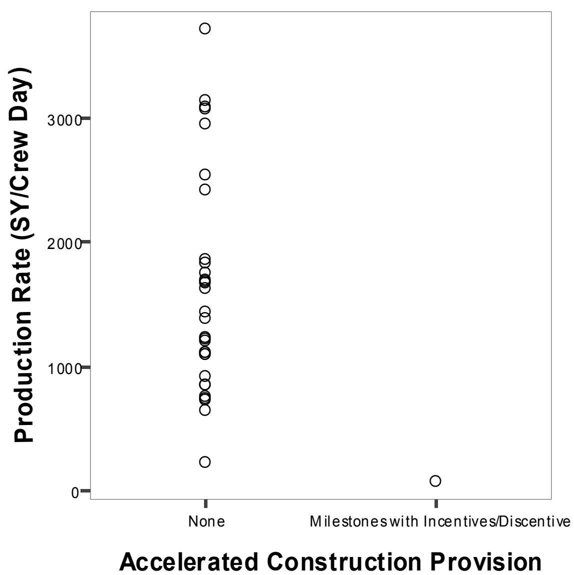


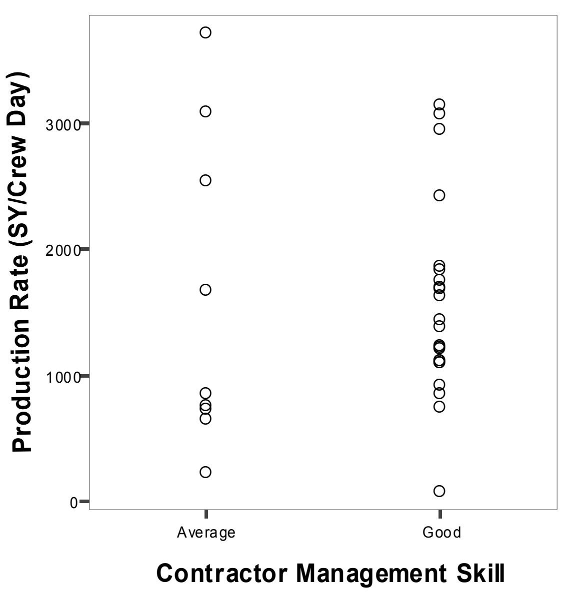
Appendix M. Lime-Treated Sub-grade: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)



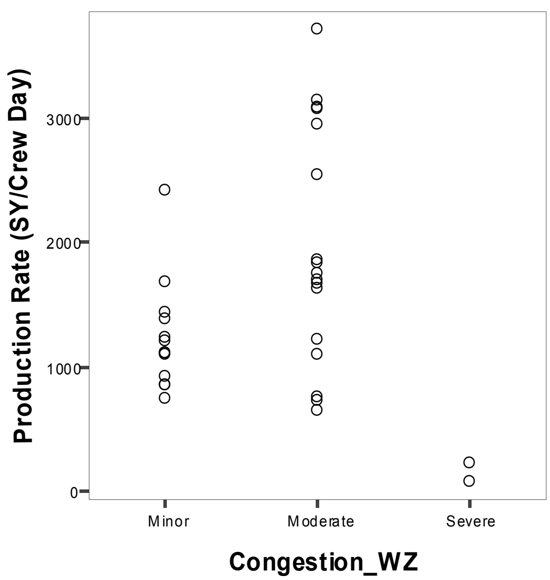


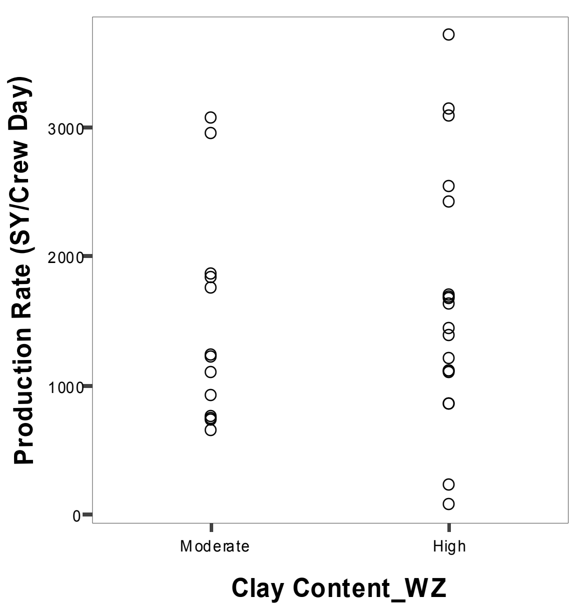
Appendix M. Lime-Treated Sub-grade: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)



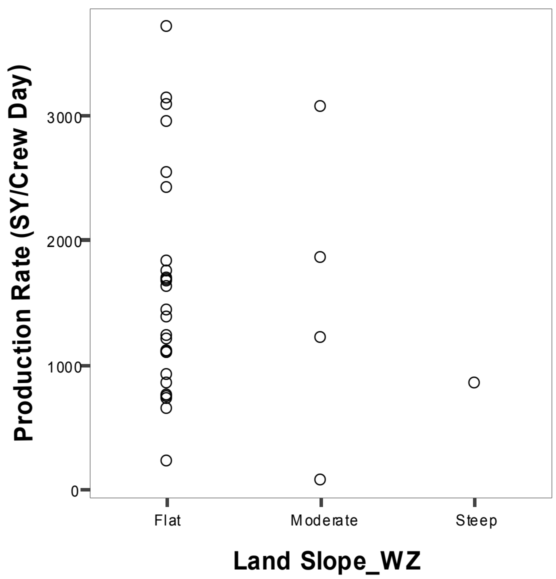


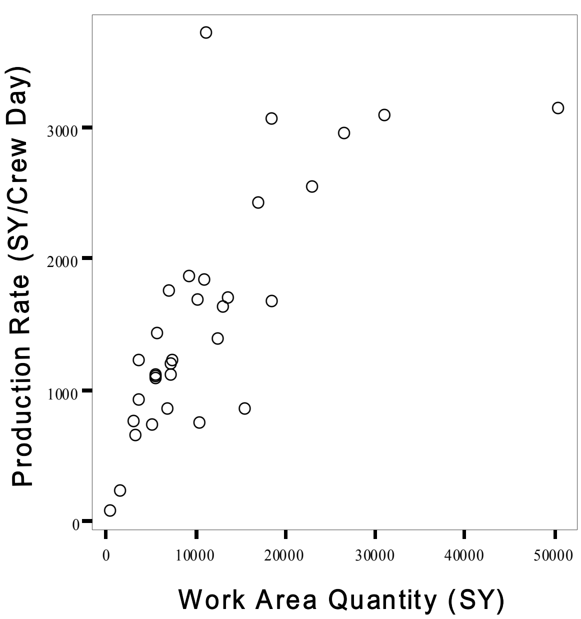
Appendix M. Lime-Treated Sub-grade: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)



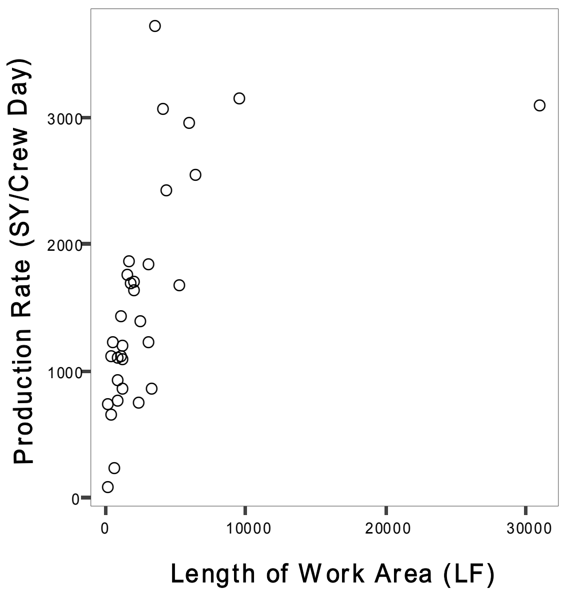


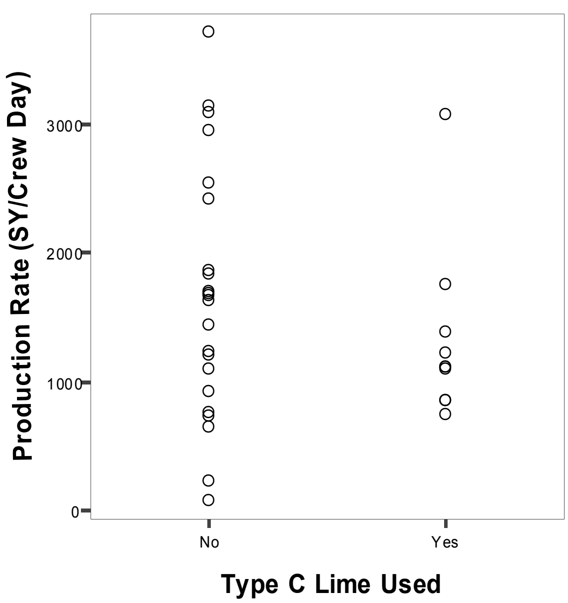
Appendix M. Lime-Treated Sub-grade: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)



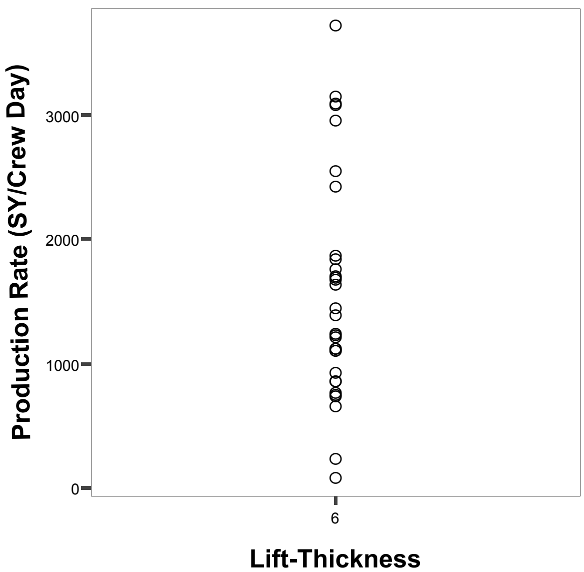


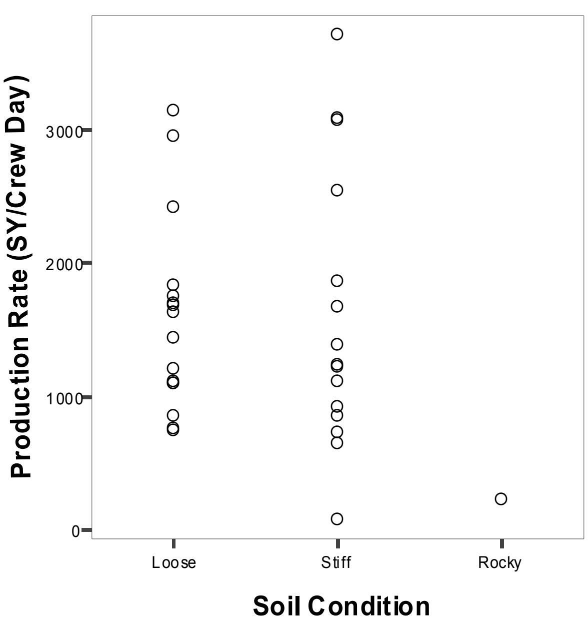
Appendix M. Lime-Treated Sub-grade: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)



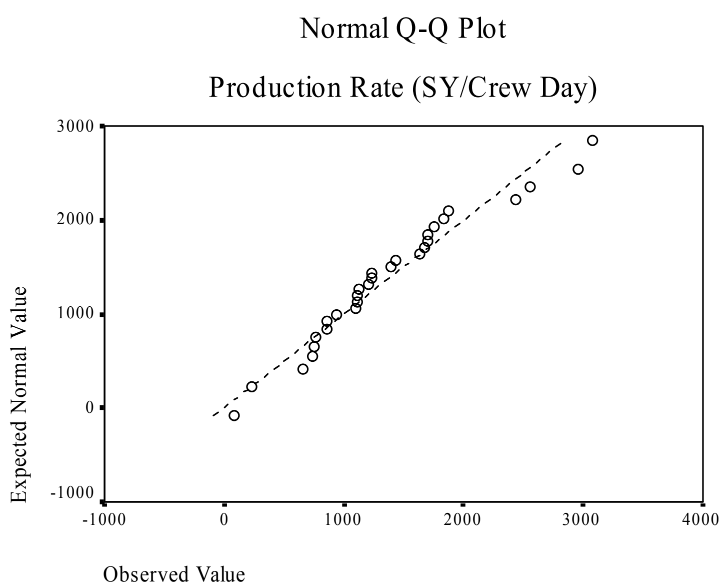


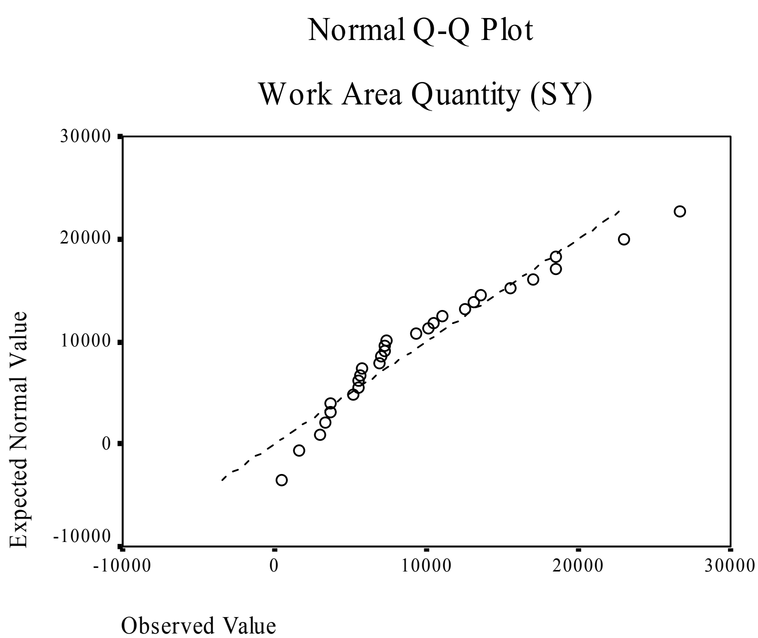
Appendix M. Lime-Treated Sub-grade: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)



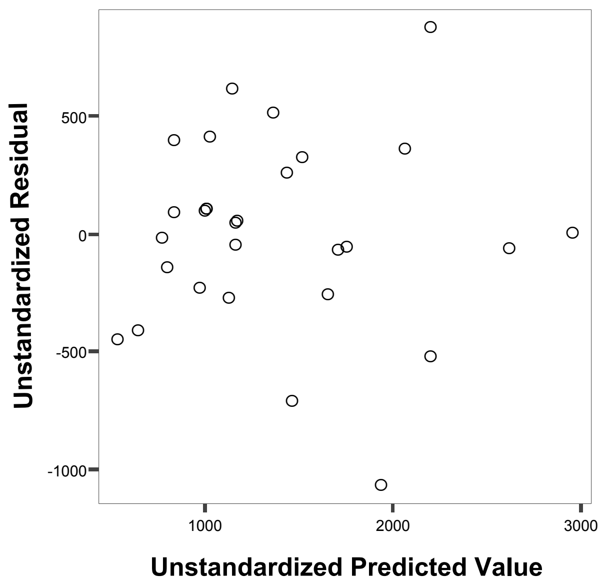


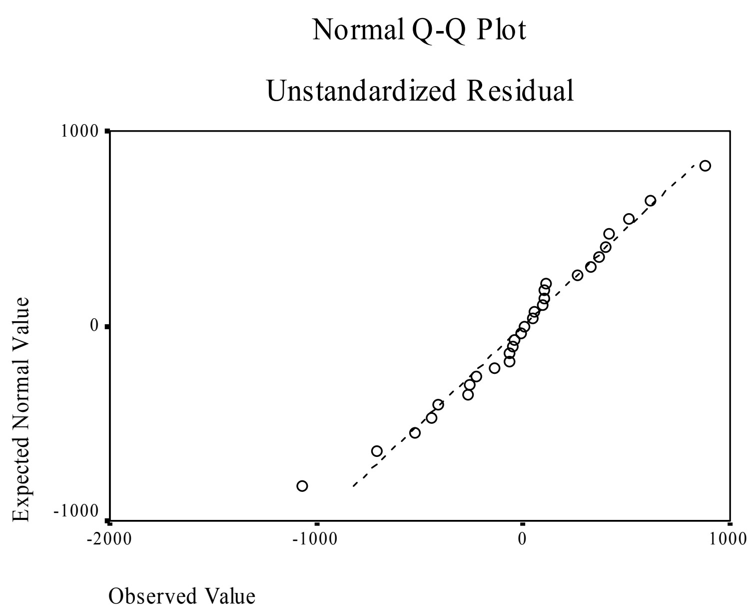
Appendix N-1. Results of Testing Assumptions of the Regression Analysis for Lime-Treated Sub-grade: Production Rates and Work Area Quantity



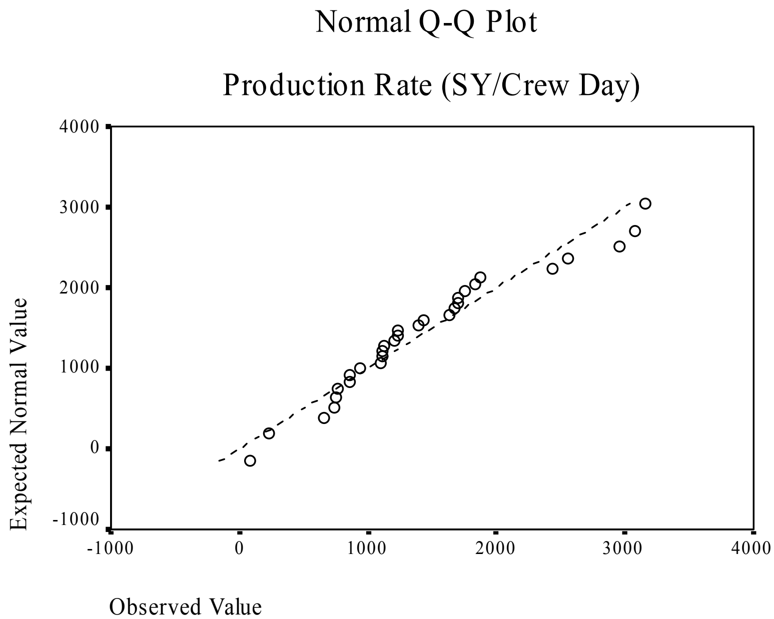


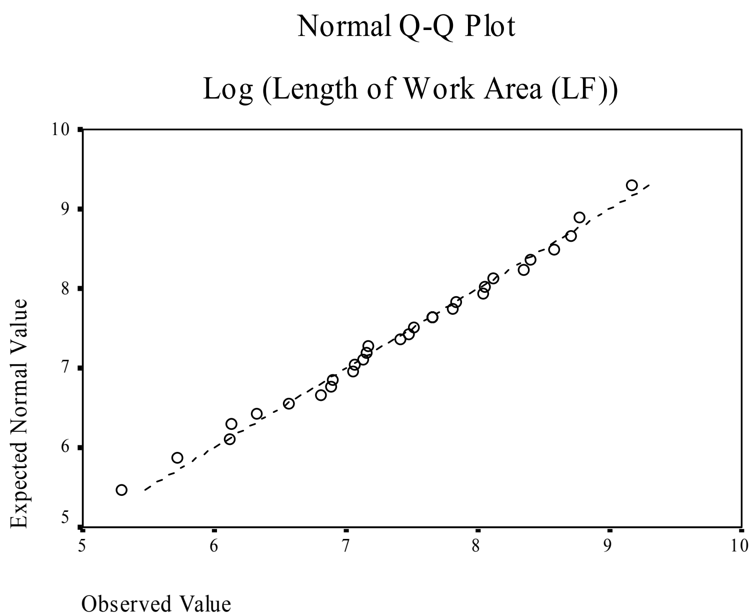
Appendix N-1. Results of Testing Assumptions of the Regression Analysis for Lime-Treated Sub-grade: Production Rates and Work Area Quantity (Cont'd)



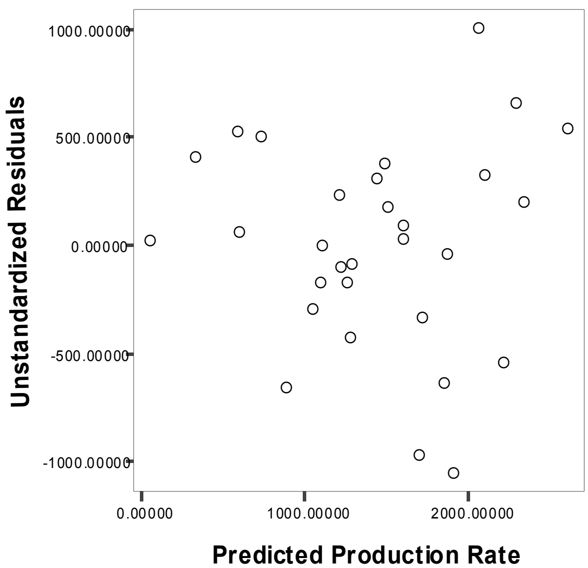


Appendix N-2. Results of Testing Assumptions of the Regression Analysis for Lime-Treated Sub-grade: Production Rates vs. Length of Work Area



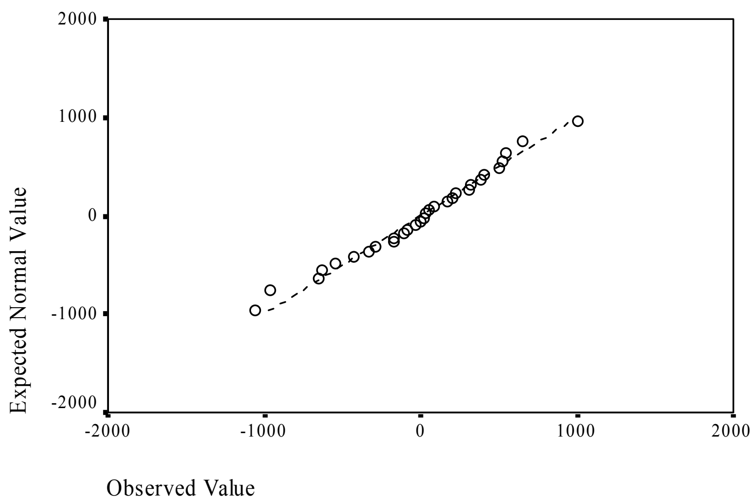


Appendix N-2. Results of Testing Assumptions of the Regression Analysis for Lime-Treated Sub-grade: Production Rates vs. Length of Work Area (Cont'd)

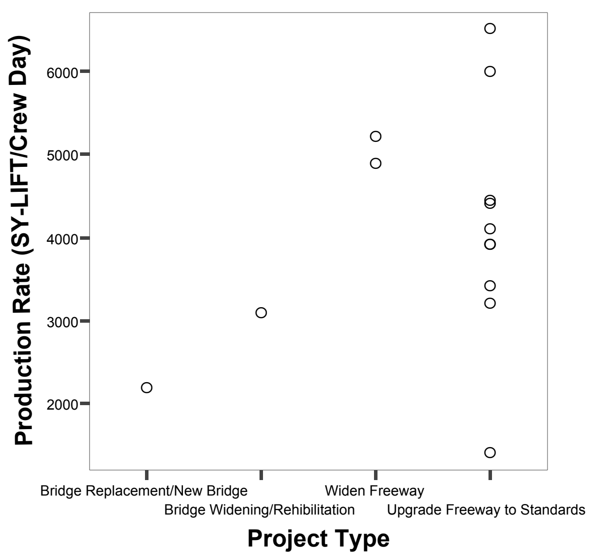


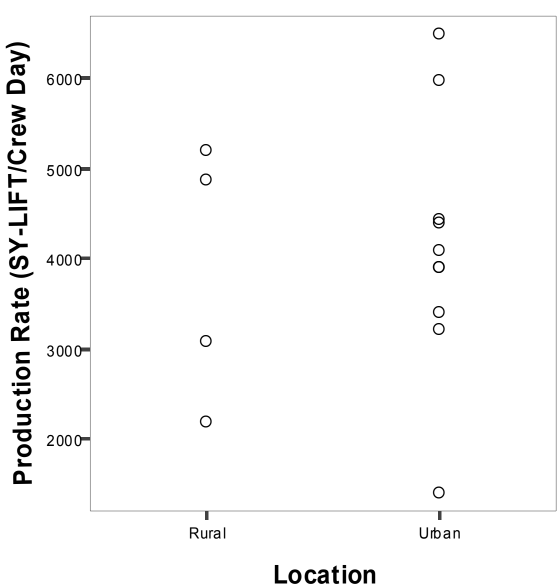
Normal Q-Q Plot

Unstandardized Residuals

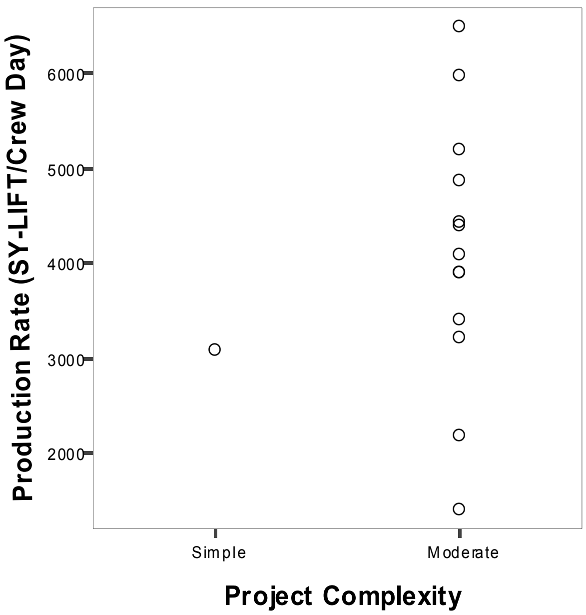


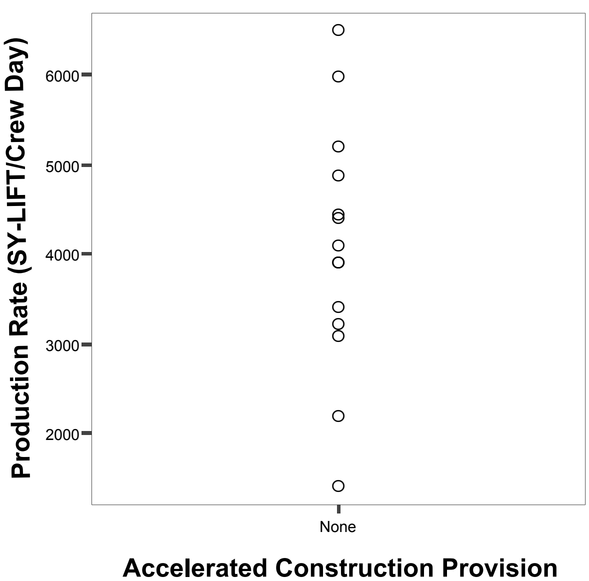
Appendix O. Cement-Treated Base: Scatter Plots of Observed Production Rates vs. Candidate Drivers



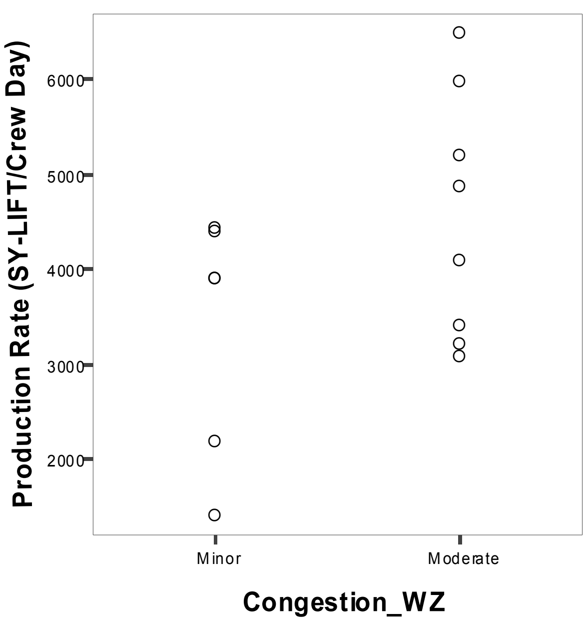


Appendix O. Cement-Treated Base: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)

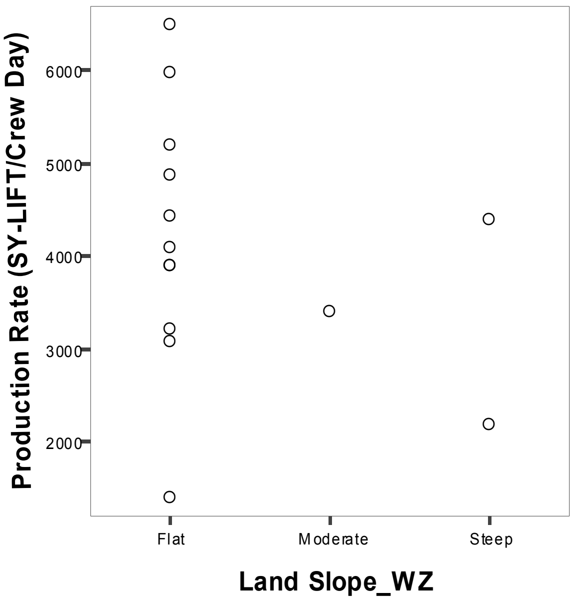


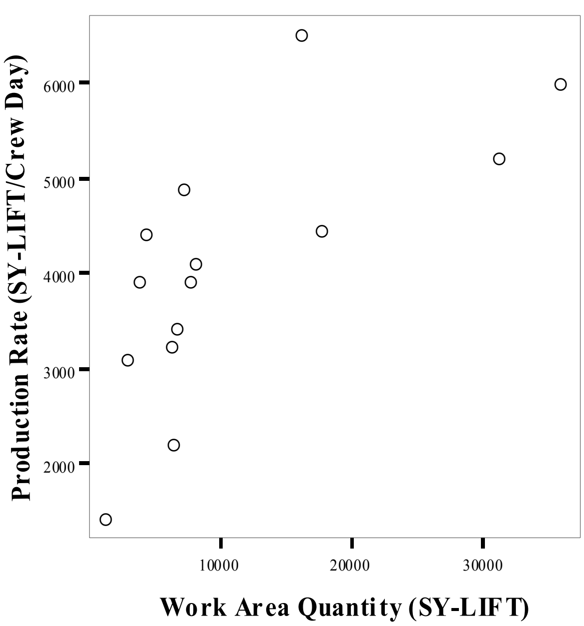


Appendix O. Cement-Treated Base: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)

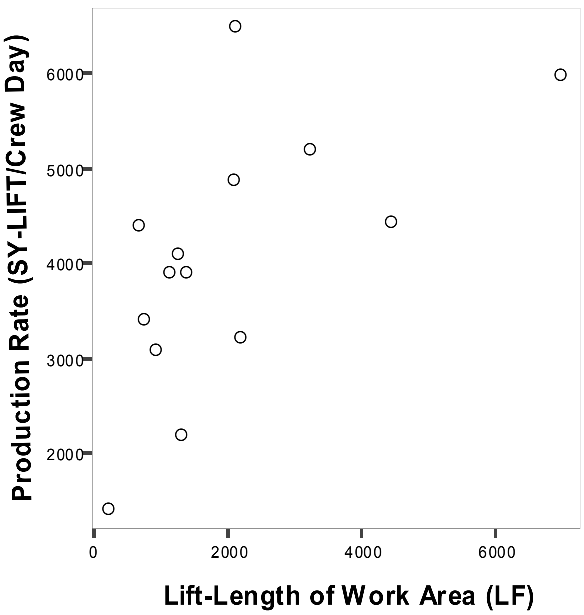


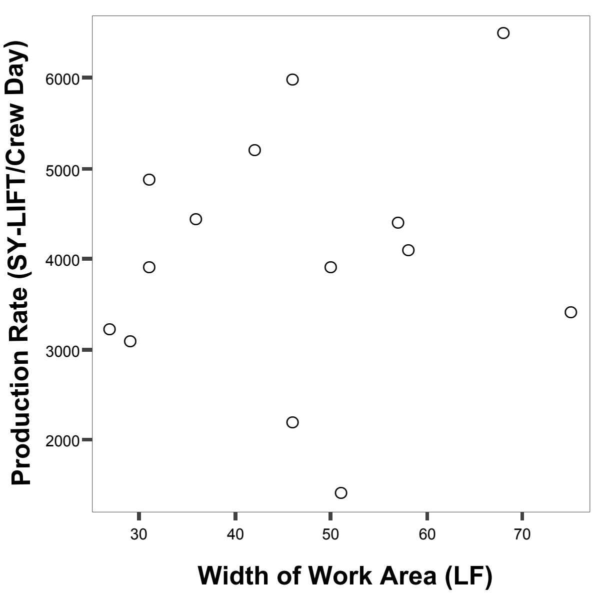
Appendix O. Cement-Treated Base: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)



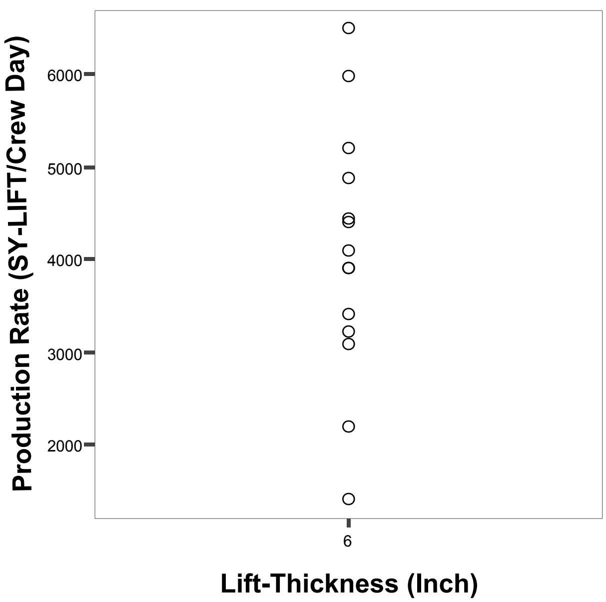


Appendix O. Cement-Treated Base: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)

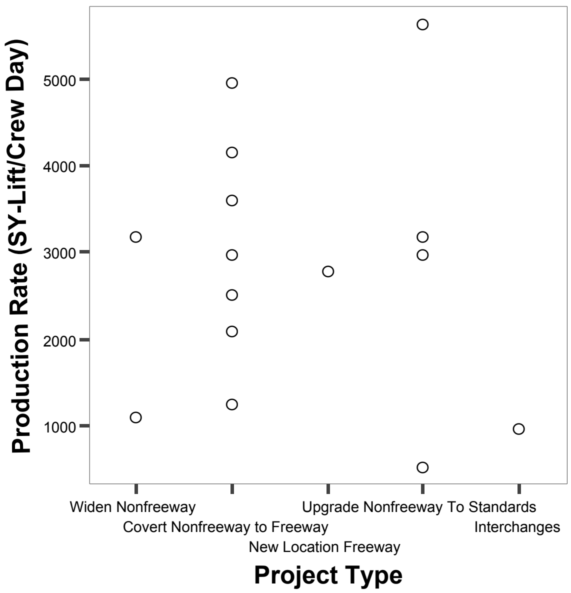


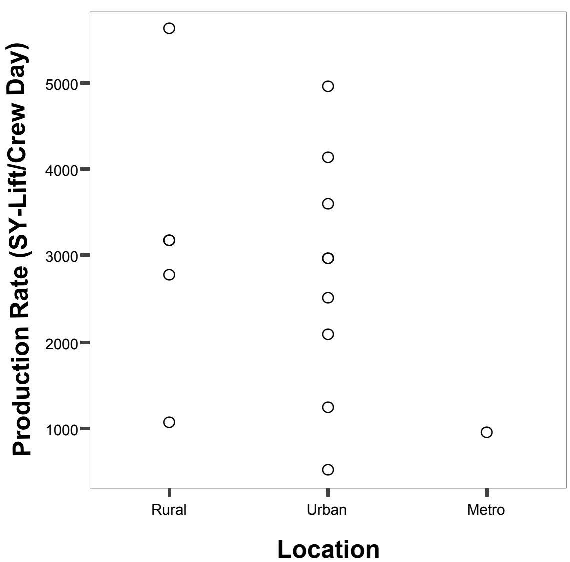


Appendix O. Cement-Treated Base: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)

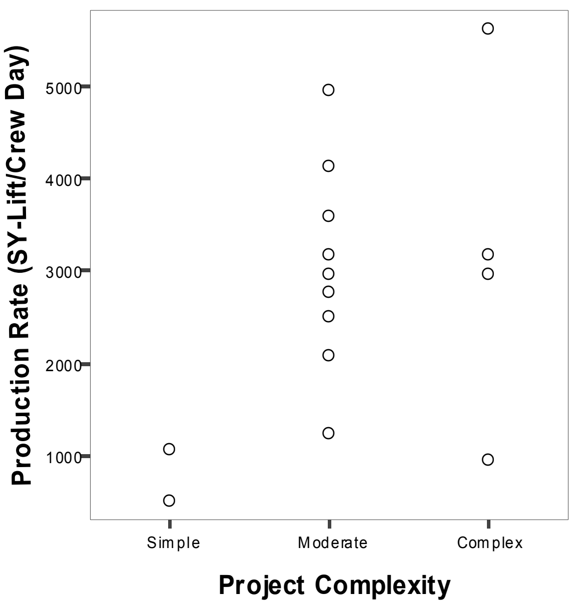


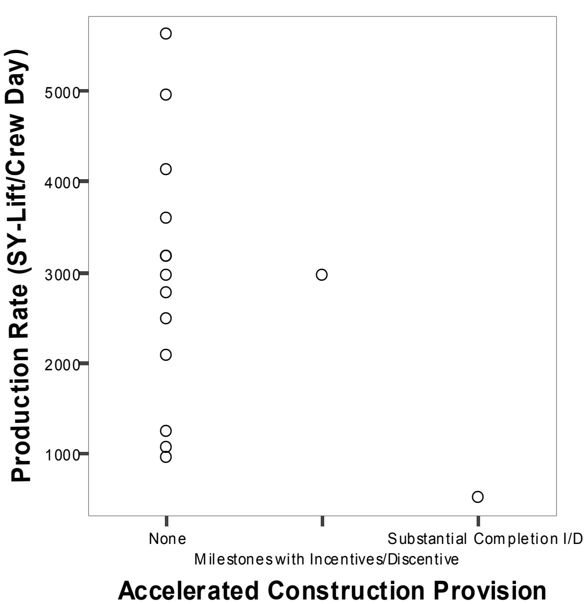
Appendix P. Flexible Base: Scatter Plots of Observed Production Rates vs. Candidate Drivers



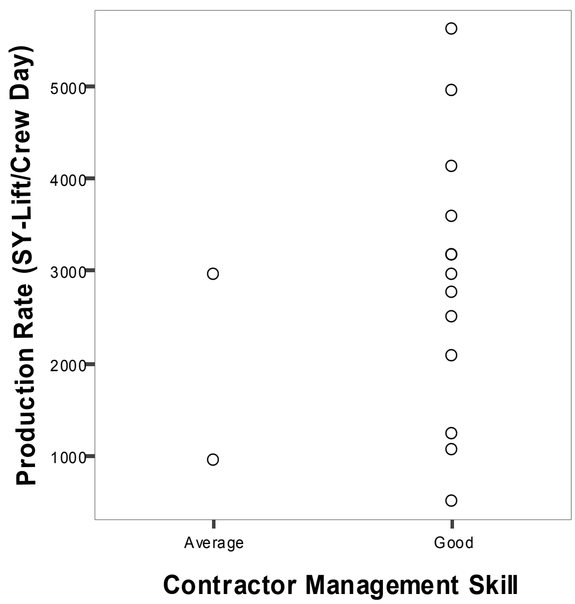


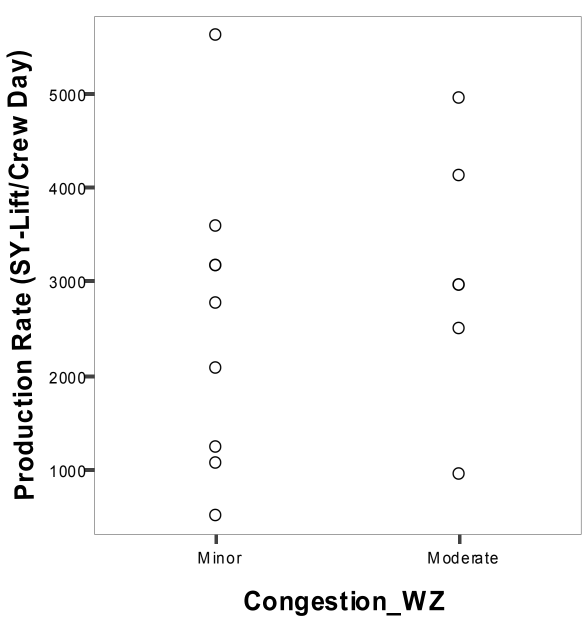
Appendix P. Flexible Base: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)



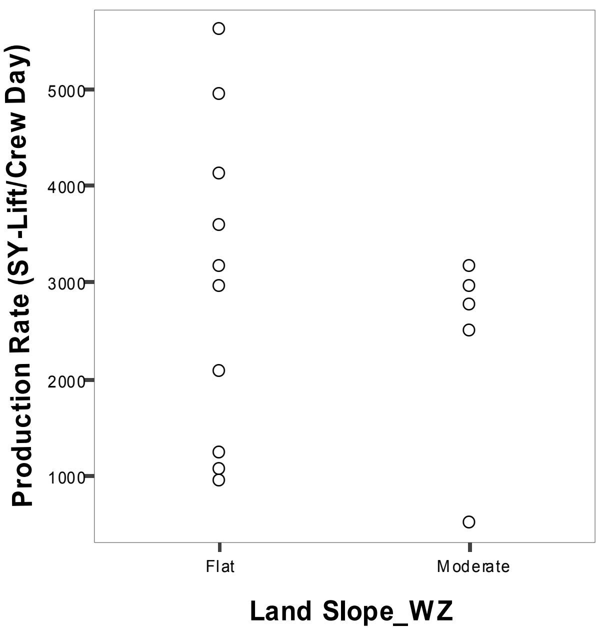


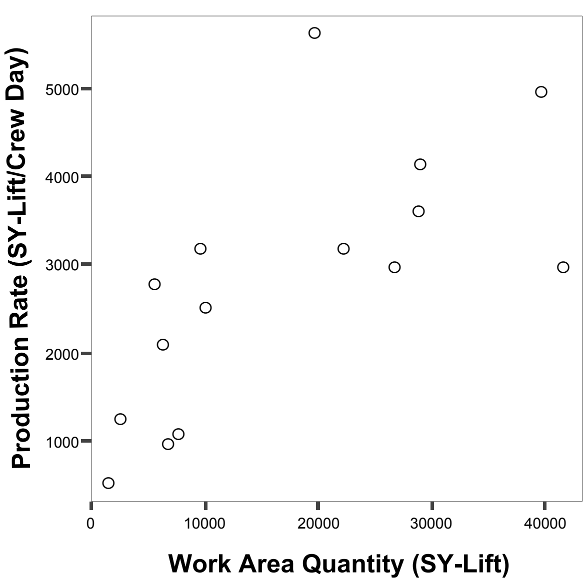
Appendix P. Flexible Base: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)



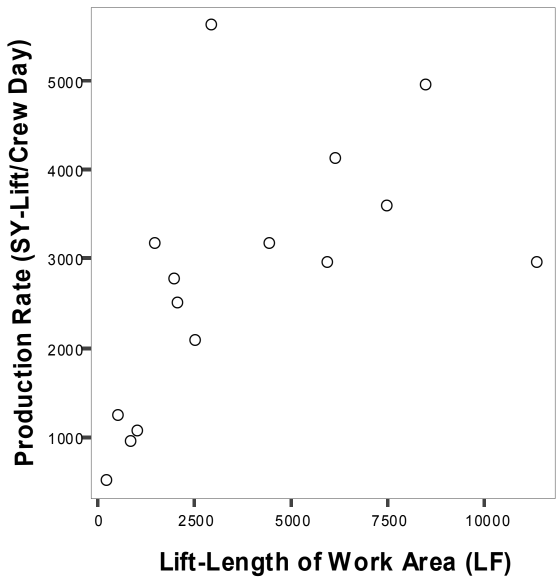


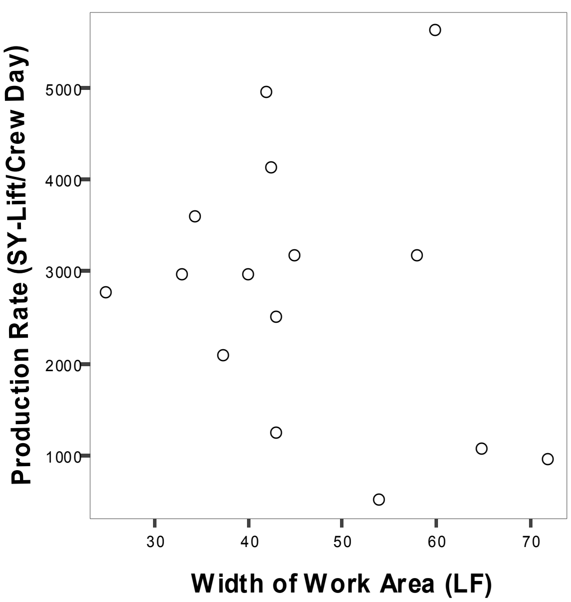
Appendix P. Flexible Base: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)



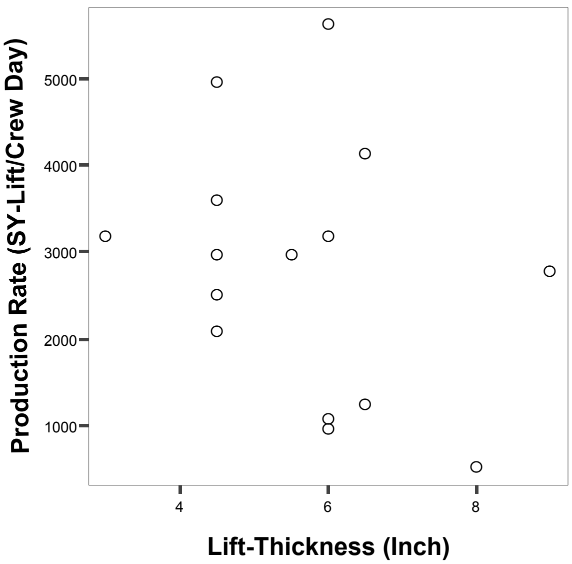


Appendix P. Flexible Base: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)





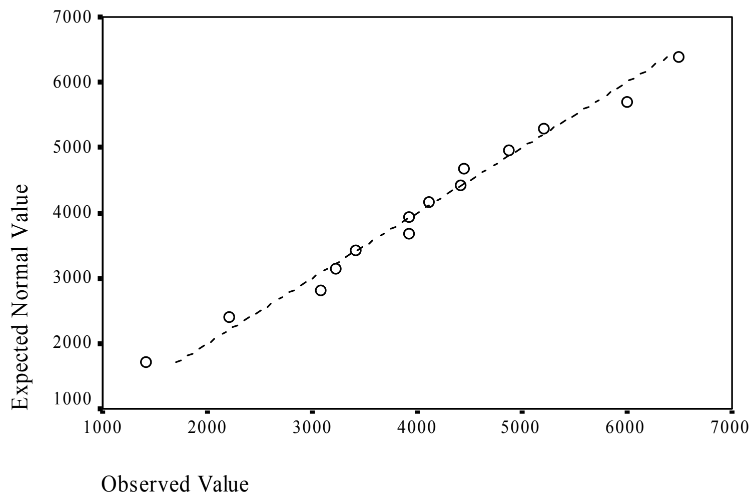
Appendix P. Flexible Base: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)



Appendix Q-1. Results of Testing Assumptions of the Regression Analysis for Cement-Treated Base: Production Rates vs. Work Area Quantity

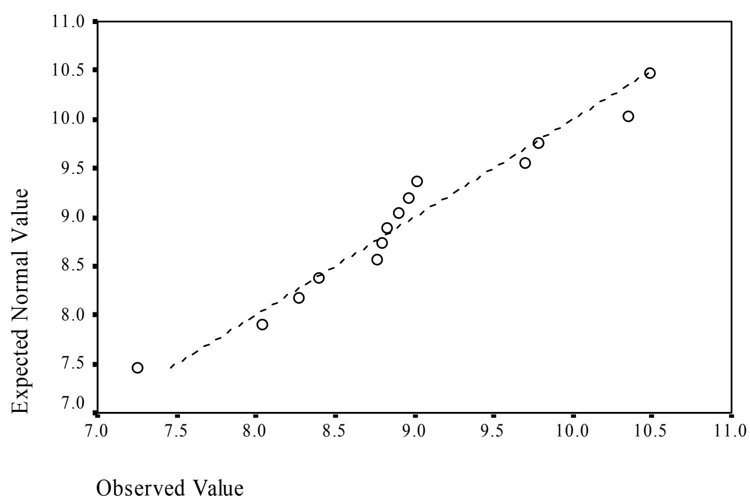
Normal Q-Q Plot

Production Rate (SY-LIFT/Crew Day)

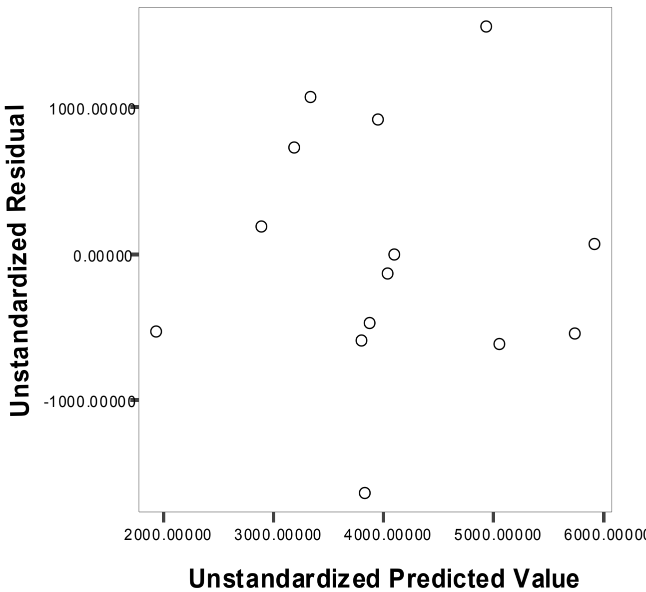


Normal Q-Q Plot

Log (Work Area Quantitty)

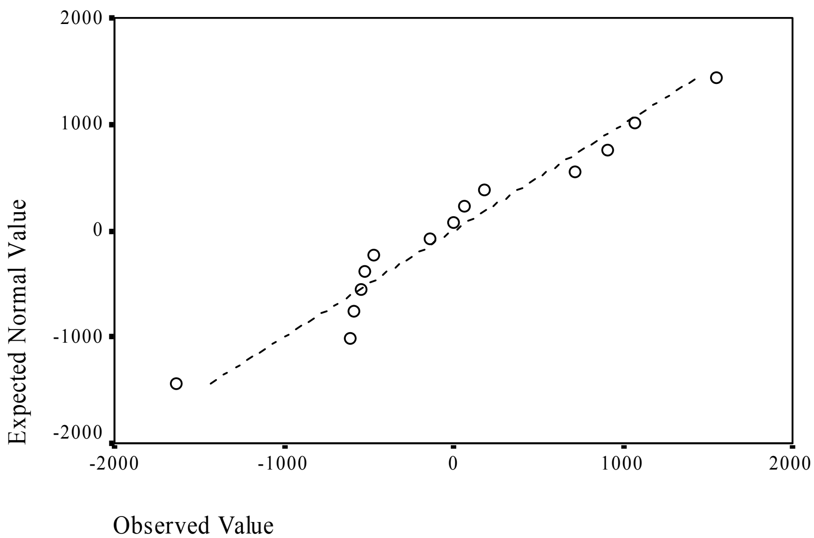


Appendix Q-1. Results of Testing Assumptions of the Regression Analysis for Cement-Treated Base: Production Rates vs. Work Area Quantity (Cont'd)

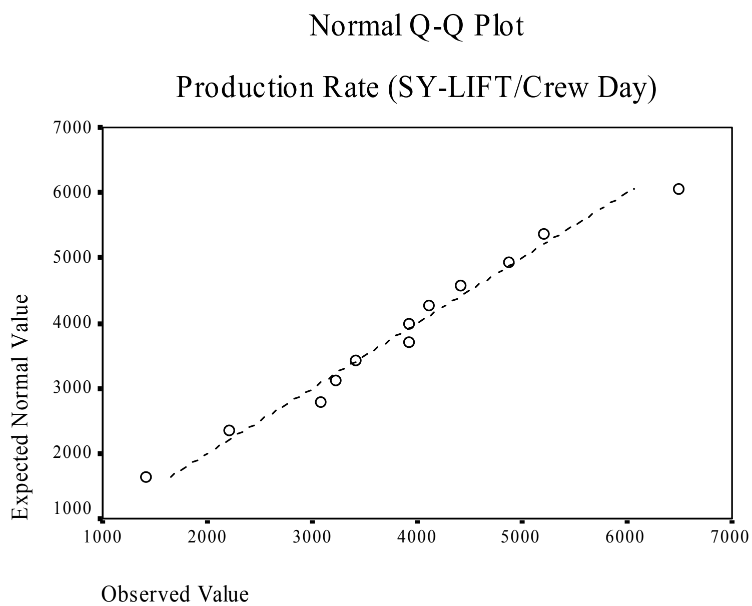


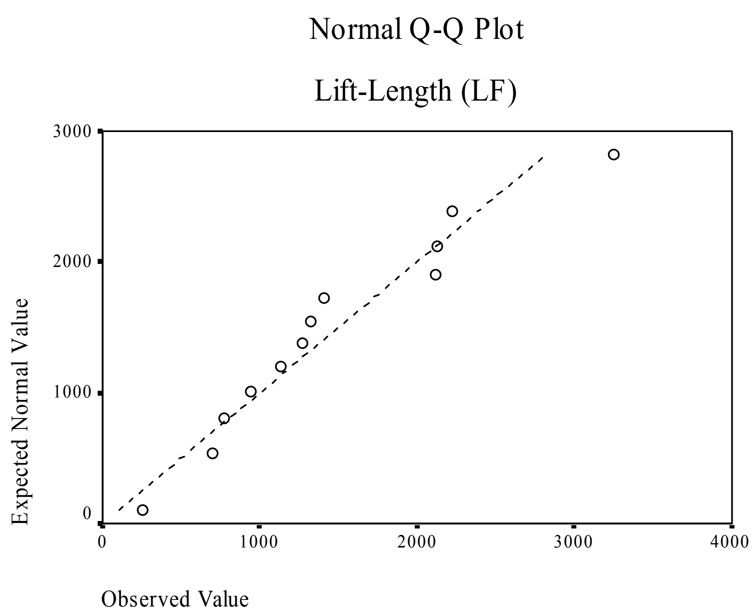
Normal Q-Q Plot

Unstandardized Residual

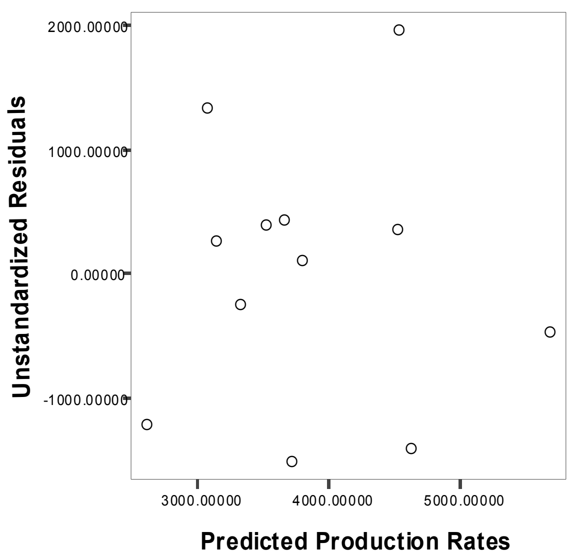


Appendix Q-2. Results of Testing Assumptions of the Regression Analysis for Cement-Treated Base: Production Rates vs. Lift-Length of Work Area



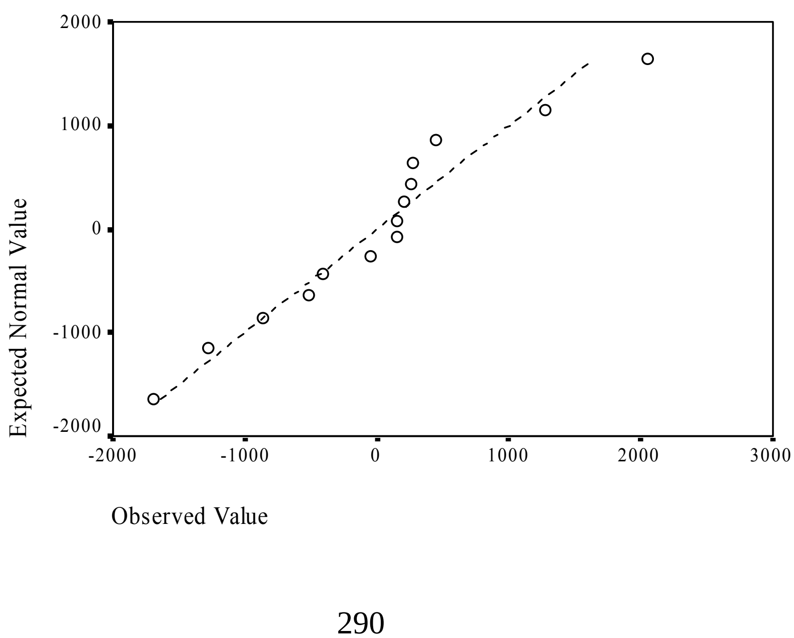


Appendix Q-2. Results of Testing Assumptions of the Regression Analysis for Cement-Treated Base: Production Rates vs. Lift-Length of Work Area (Cont'd)



Normal Q-Q Plot

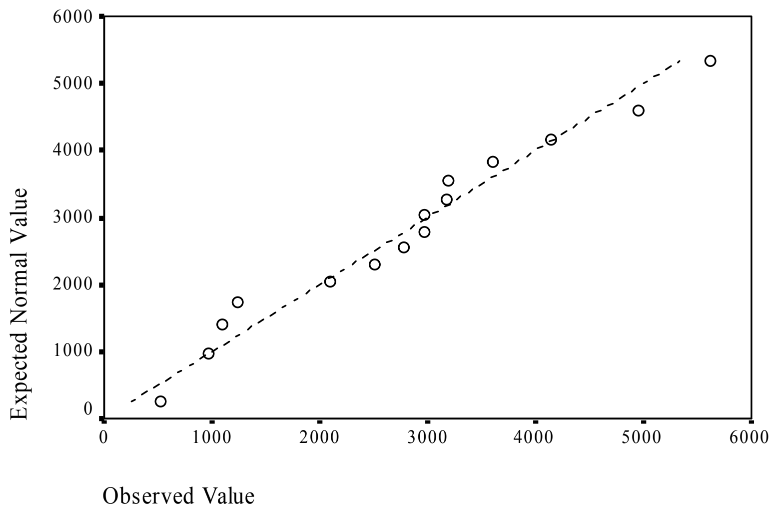
Unstandard Residuals



Appendix R-1. Results of Testing Assumptions of the Regression Analysis for Flexible Base: Production Rates vs. Work Area Quantity

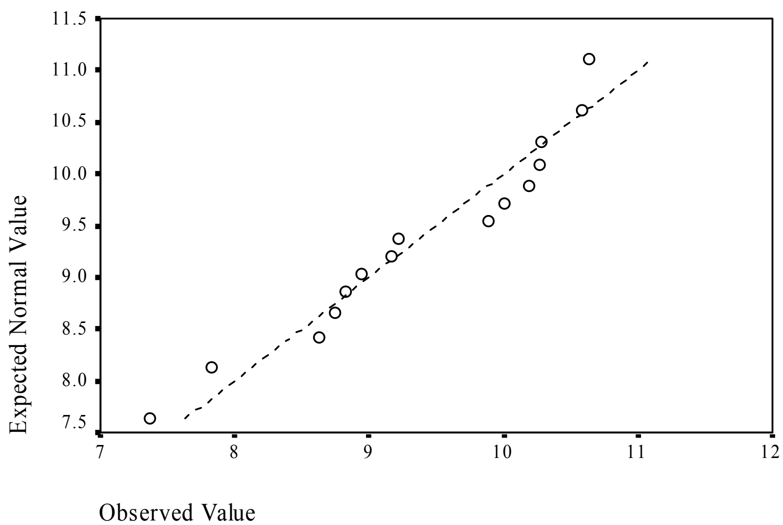
Normal Q-Q Plot

Production Rate (SY-Lift/Crew Day)

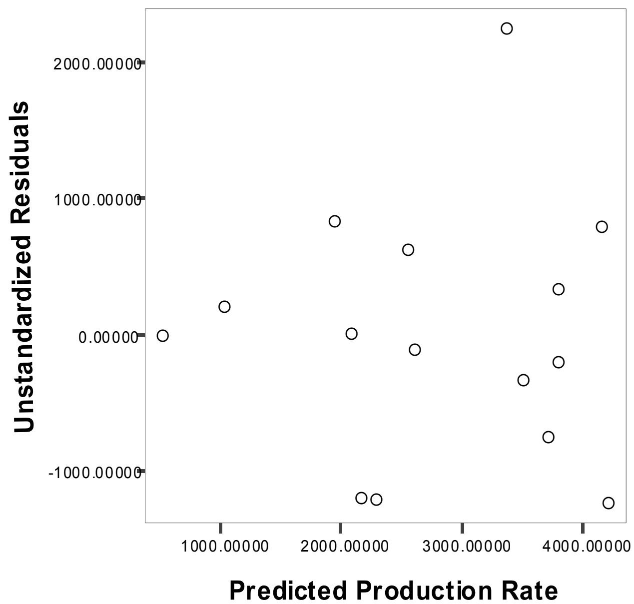


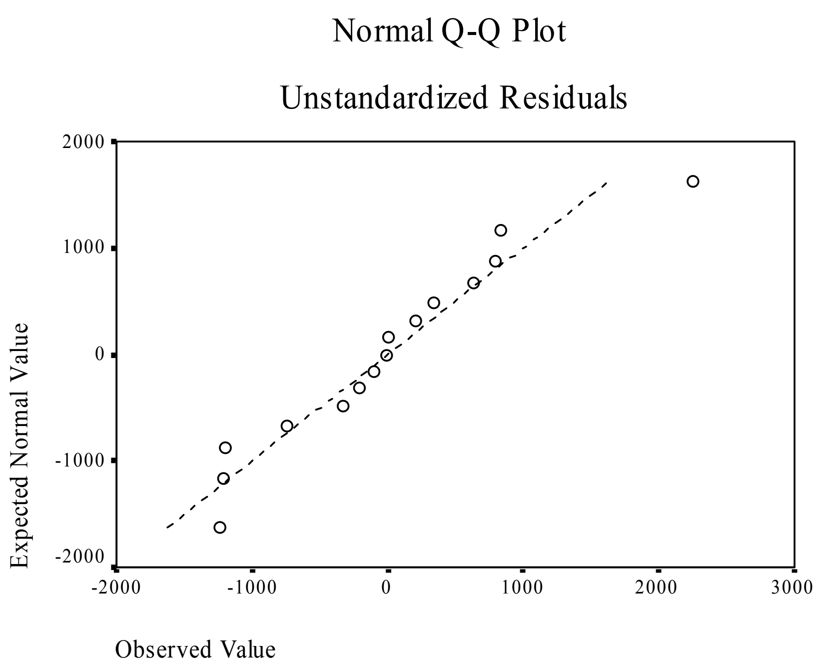
Normal Q-Q Plot

Log (Work Area Quantity)



Appendix R-1. Results of Testing Assumptions of the Regression Analysis for Flexible Base: Production Rates vs. Work Area Quantity (Cont'd)

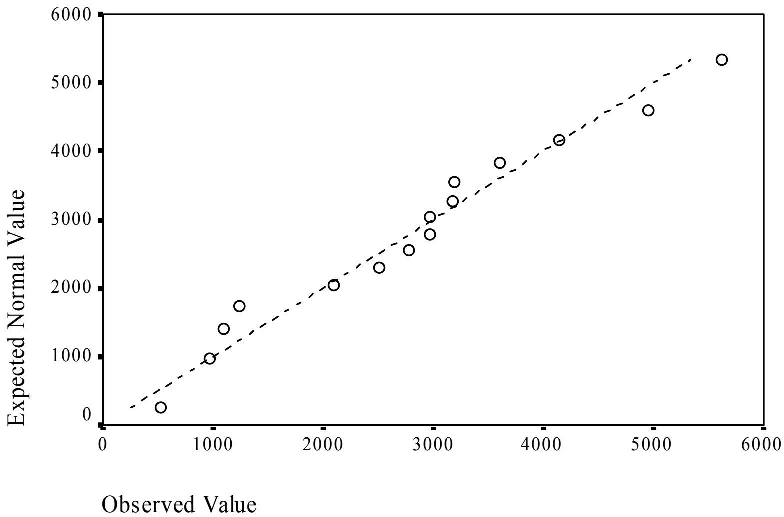




Appendix R-2. Results of Testing Assumptions of the Regression Analysis for Flexible Base: Production Rates vs. Lift-Length of Work Area

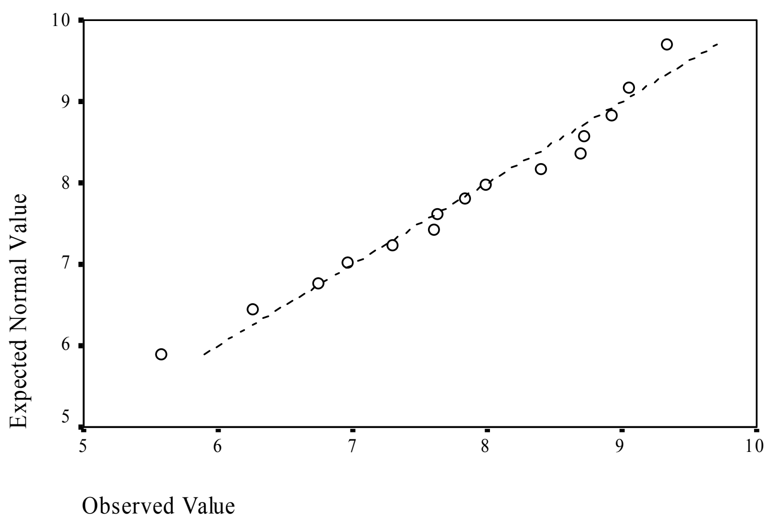
Normal Q-Q Plot

Production Rate (SY-Lift/Crew Day)

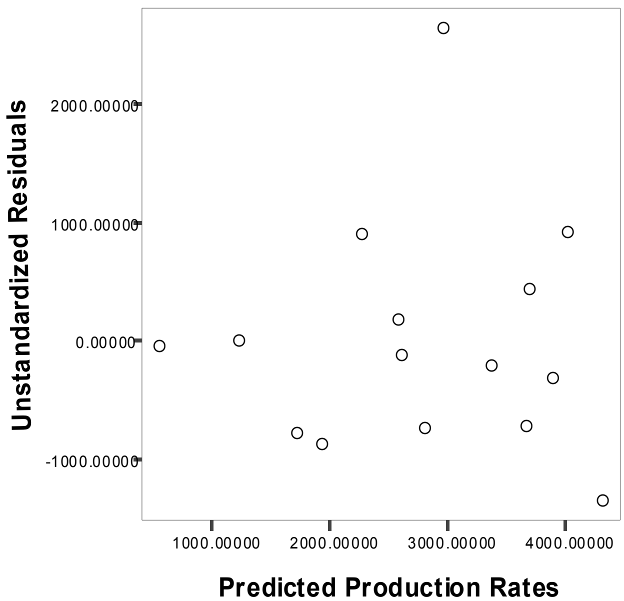


Normal Q-Q Plot

Log (Lift-Length of Work Area)

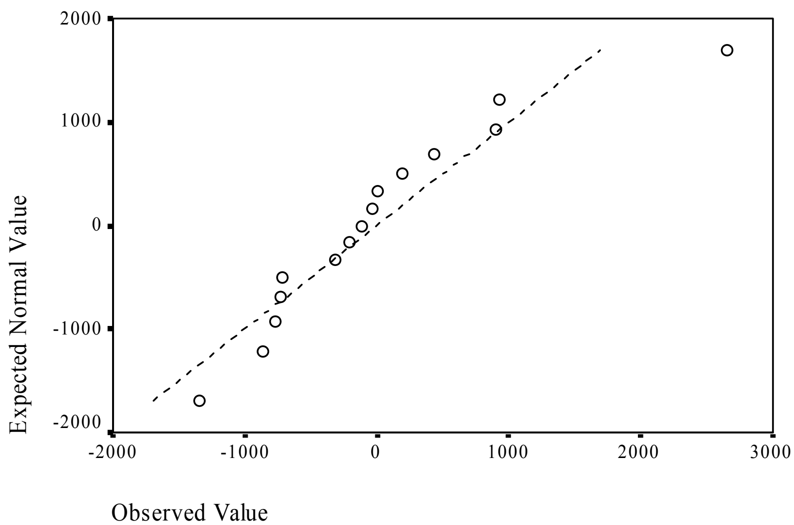


Appendix R-2. Results of Testing Assumptions of the Regression Analysis for Flexible Base: Production Rates vs. Lift-Length of Work Area (Cont'd)

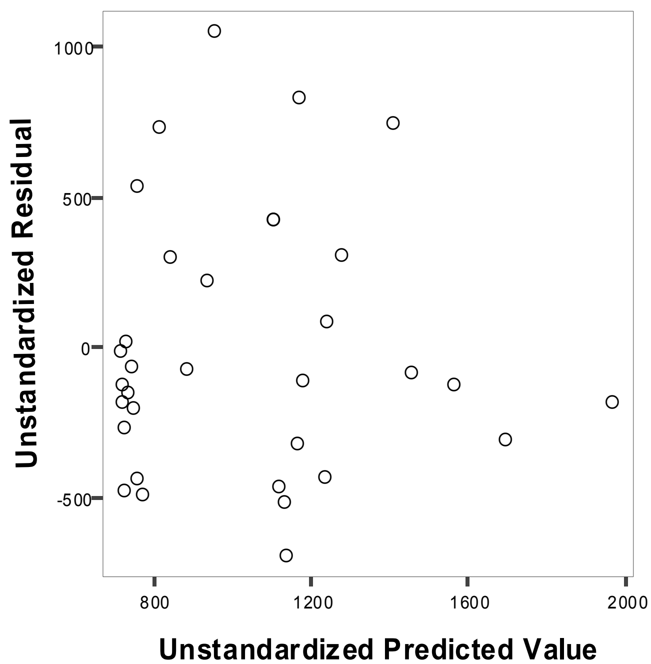


Normal Q-Q Plot

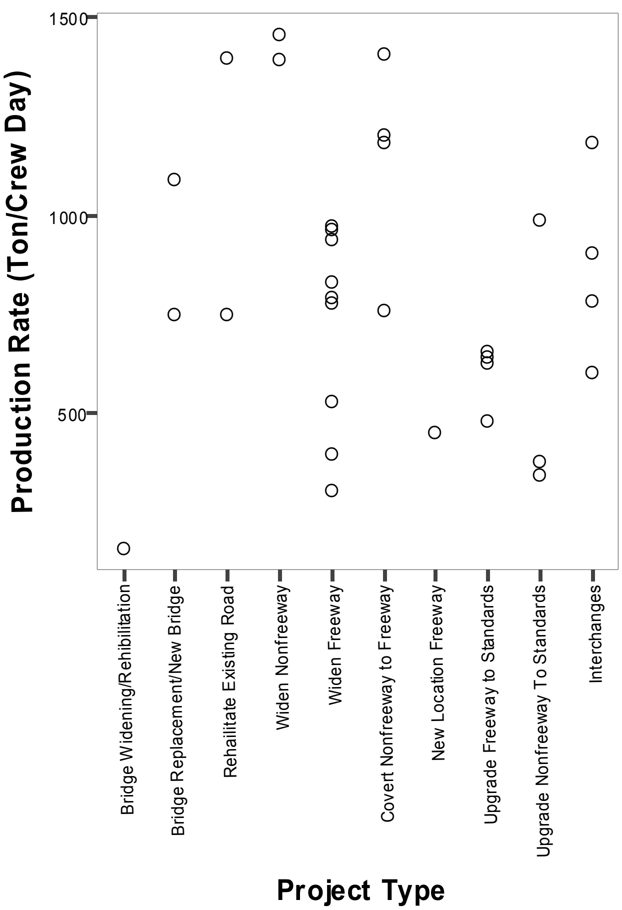
Unstandardized Residuals



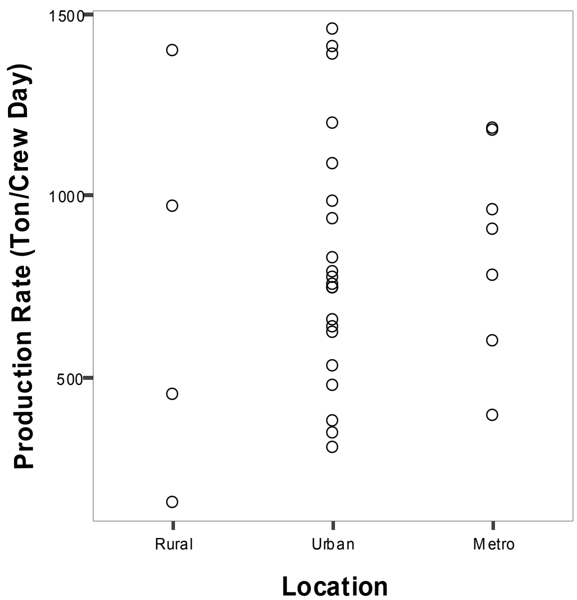
Appendix S. Results of Testing Assumptions of the Multiple Regression Analysis for Embankment:

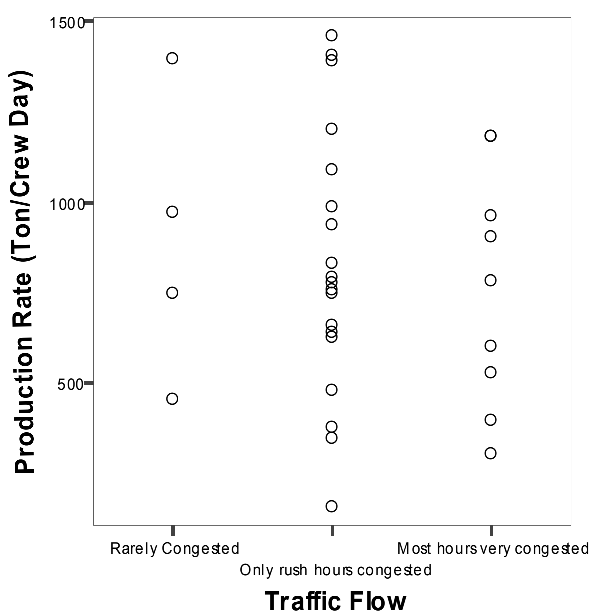


Appendix T. Hot Mix Asphalt Pavement: Scatter Plots of Observed Production Rates vs. Candidate Drivers

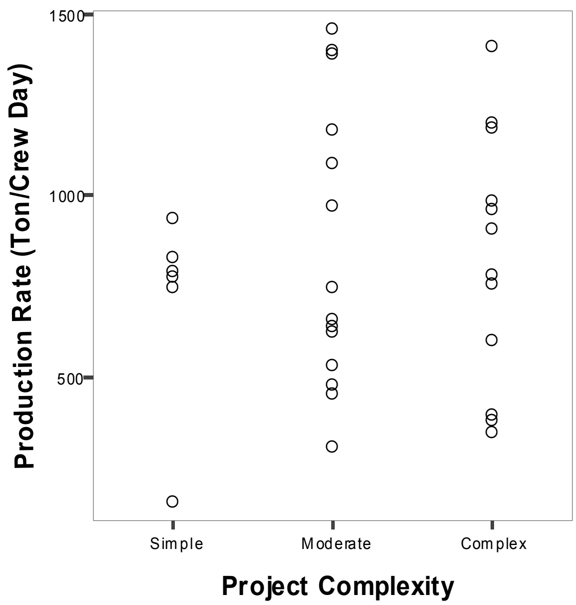


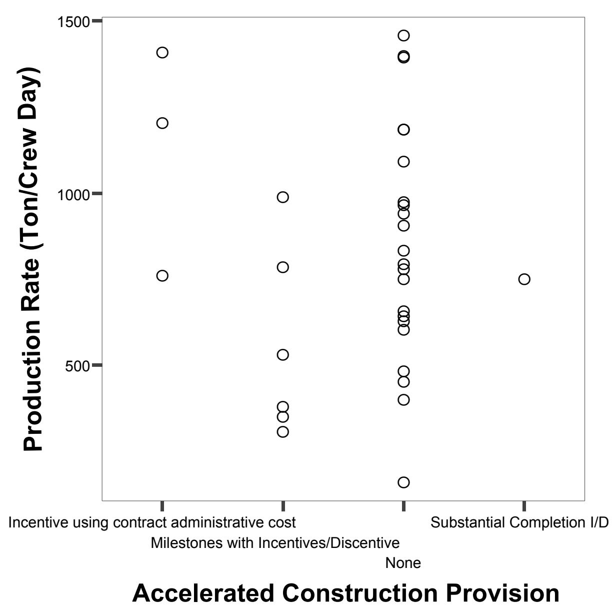
Appendix T. Hot Mix Asphalt Pavement: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)



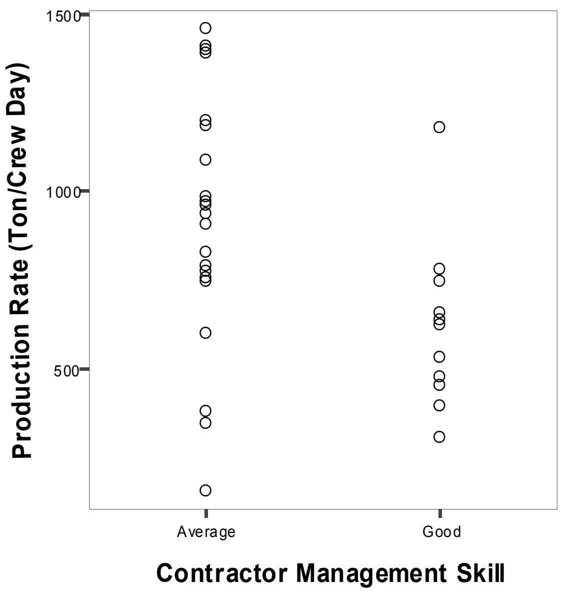


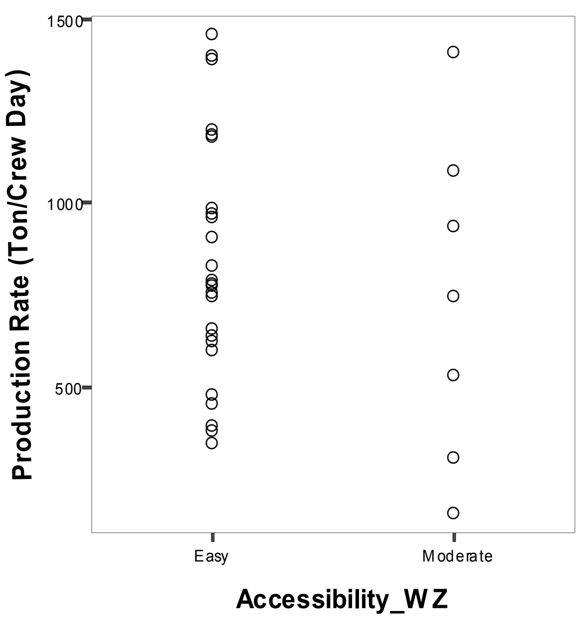
Appendix T. Hot Mix Asphalt Pavement: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)



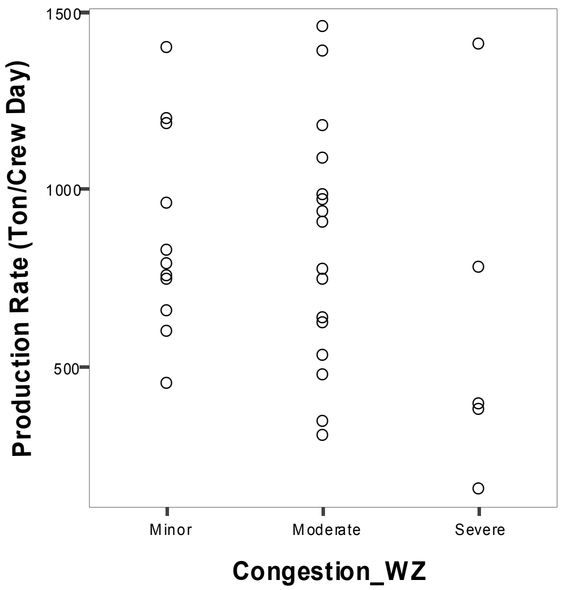


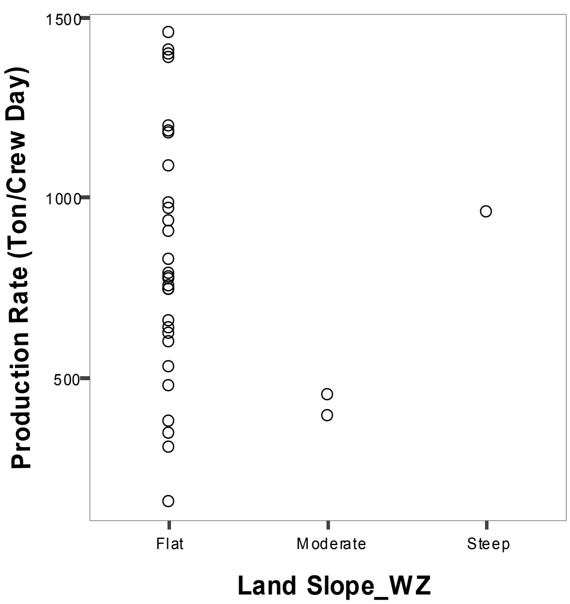
Appendix T. Hot Mix Asphalt Pavement: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)



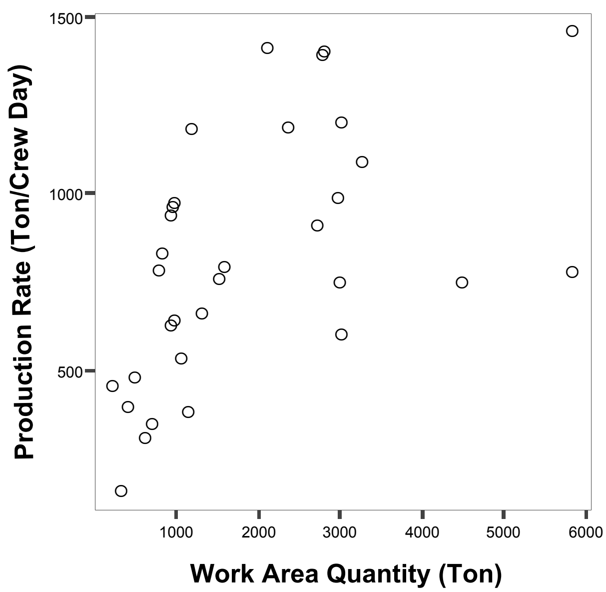


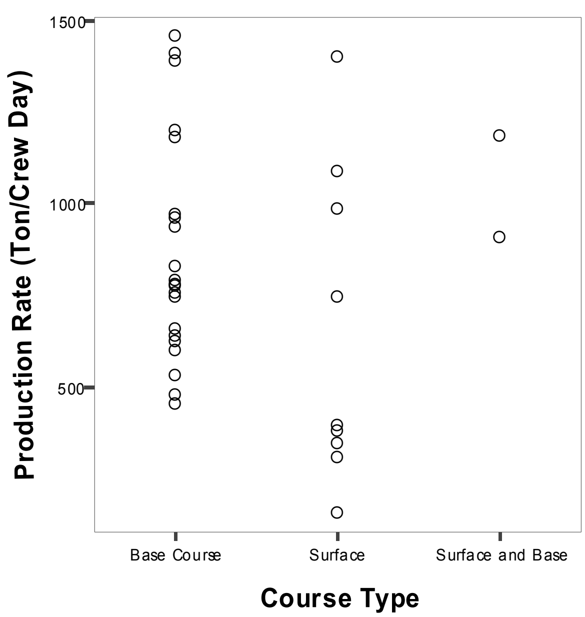
Appendix T. Hot Mix Asphalt Pavement: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)



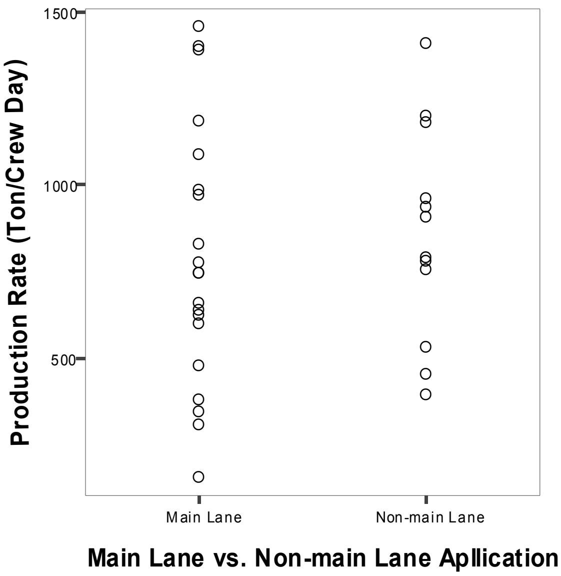


Appendix T. Hot Mix Asphalt Pavement: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)

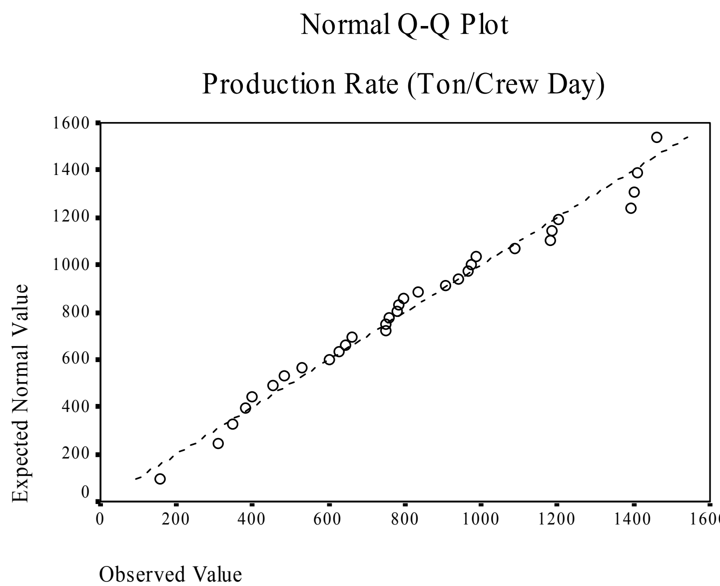


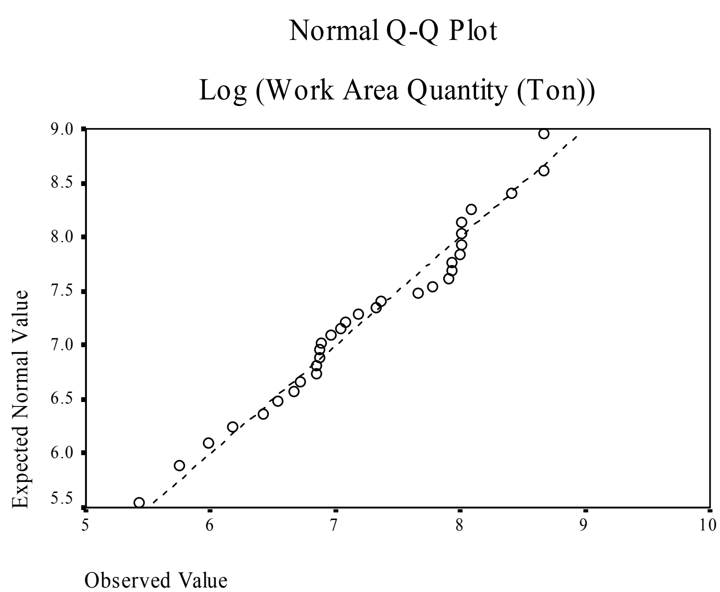


Appendix T. Hot Mix Asphalt Pavement: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)

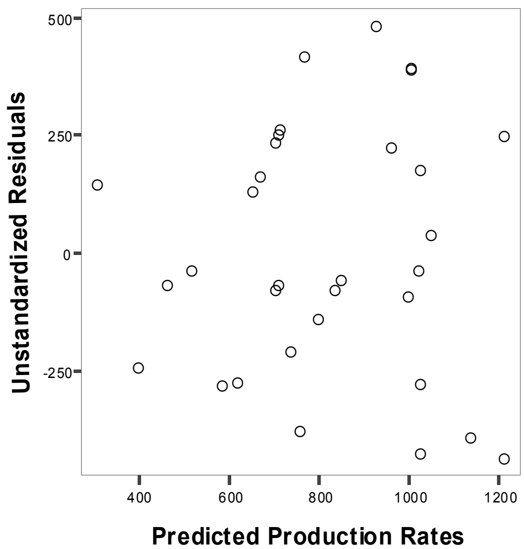


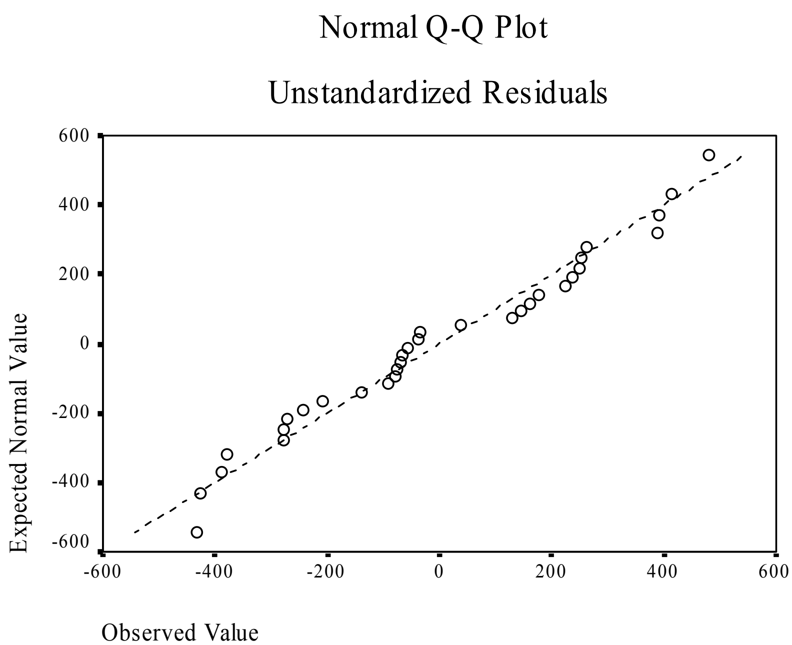
Appendix U-1. Results of Testing Assumptions of the Regression Analysis for Hot Mix Asphalt Pavement: Production Rates vs. Work Area Quantity





Appendix U-1. Results of Testing Assumptions of the Regression Analysis for Hot Mix Asphalt Pavement: Production Rates vs. Work Area Quantity (Cont'd)



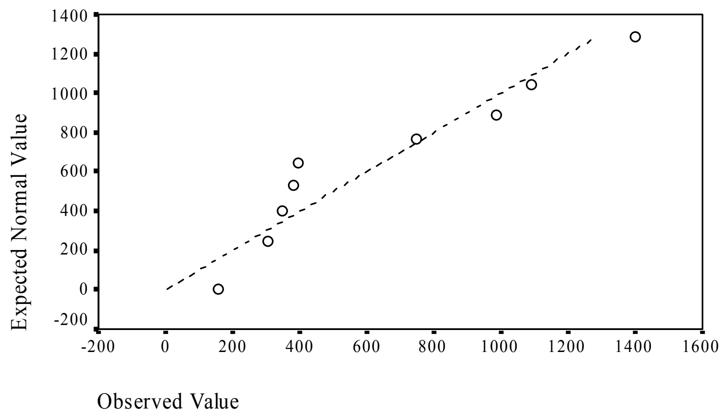


Appendix U-2. Results of Testing Normality of Variables for Hot Mix Asphalt Pavement: Production Rates by Course Types

Normal Q-Q Plot

Production Rate (Ton/Crew Day)

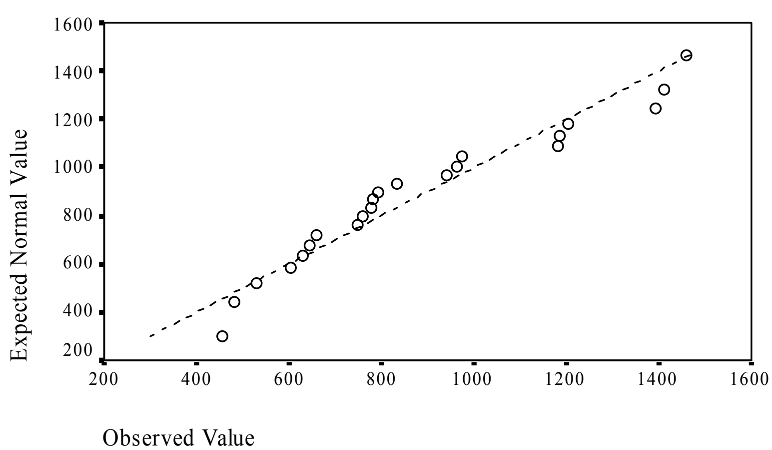
Surface



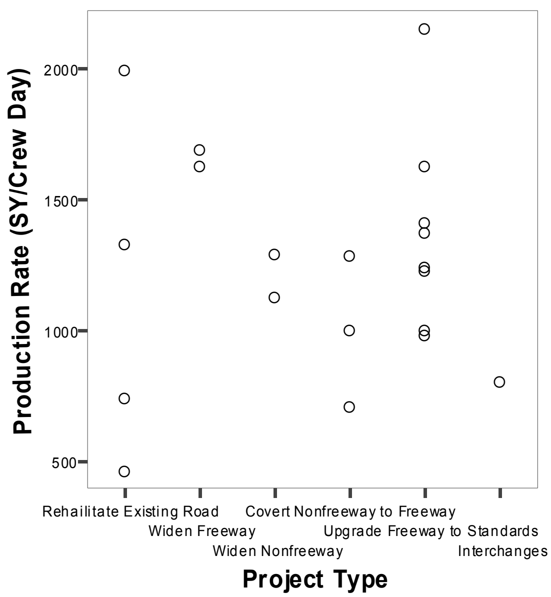
Normal Q-Q Plot

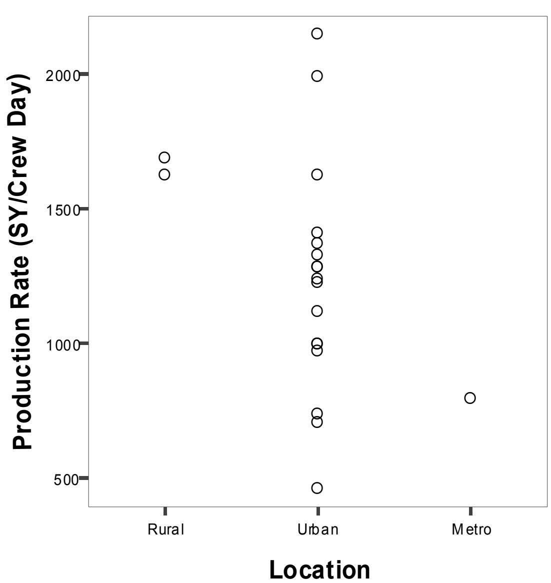
Production Rate (Ton/Crew Day)

Base Course

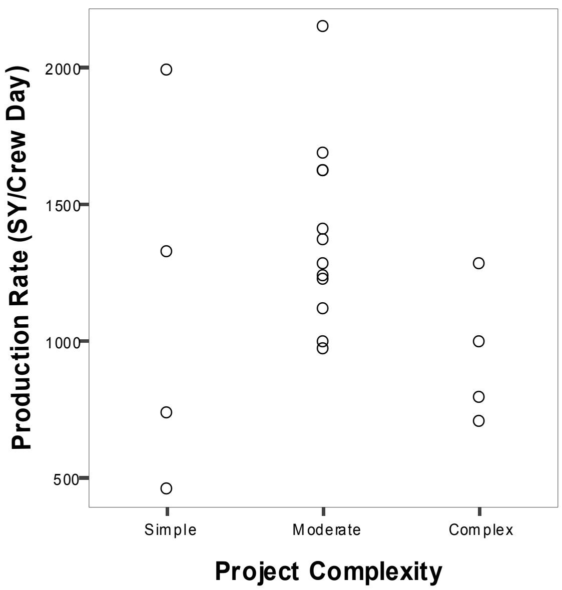


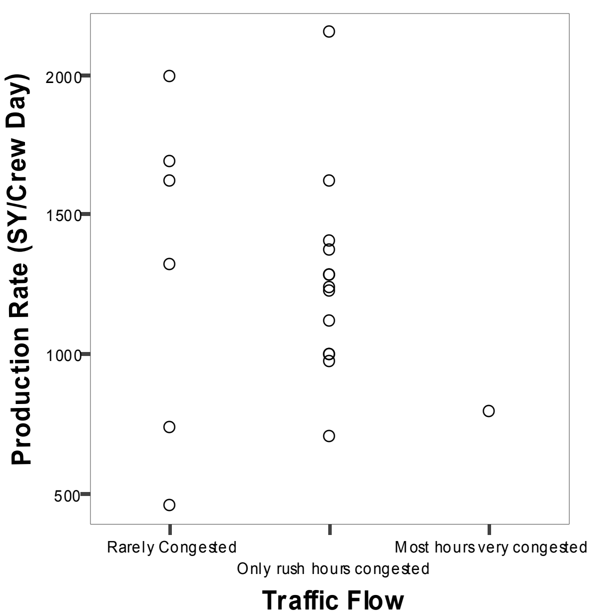
Appendix V. Slip-form Concrete Pavement: Scatter Plots of Observed Production Rates vs. Candidate Drivers



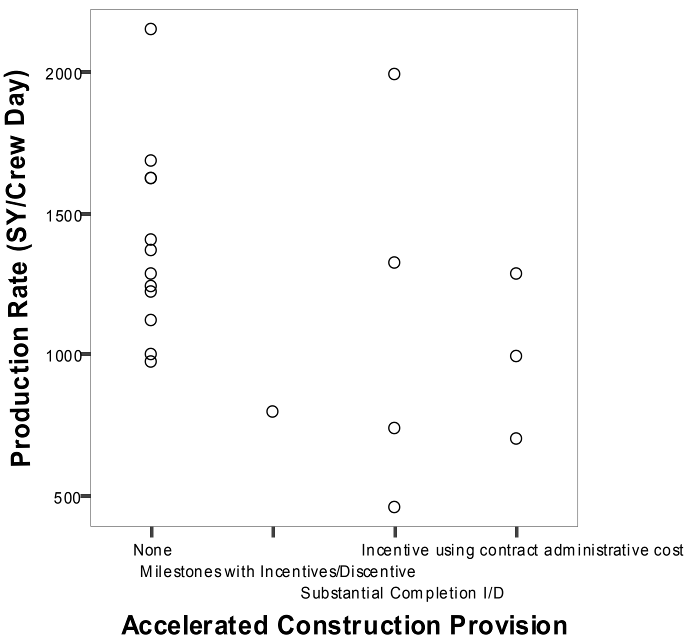


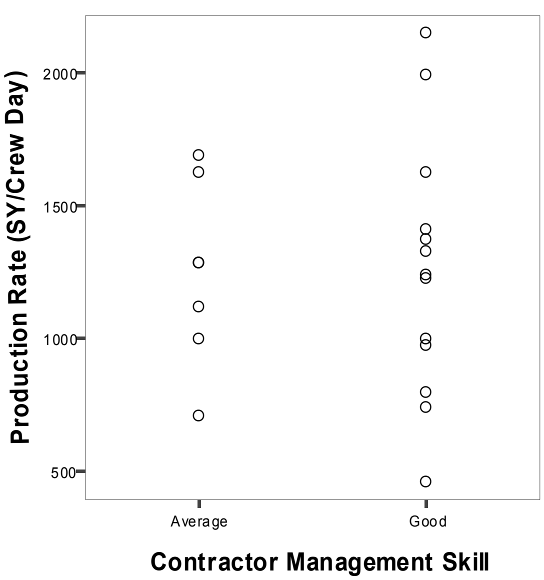
Appendix V. Slip-form Concrete Pavement: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)



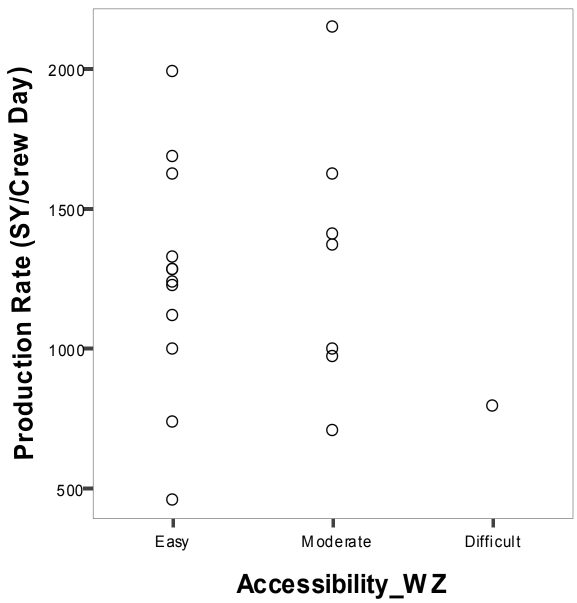


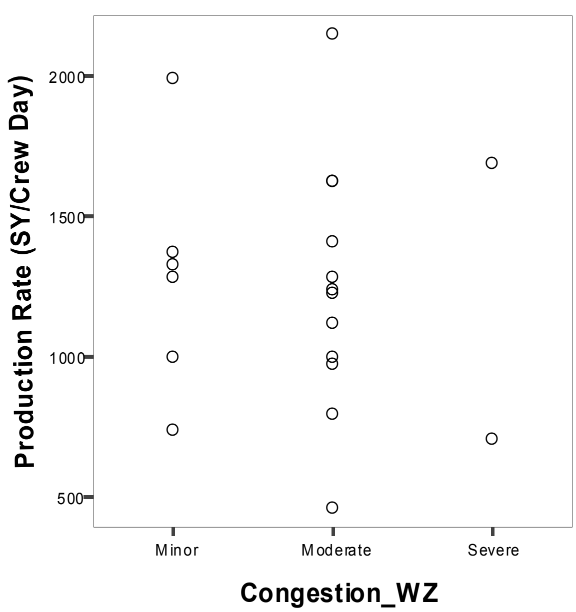
Appendix V. Slip-form Concrete Pavement: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)



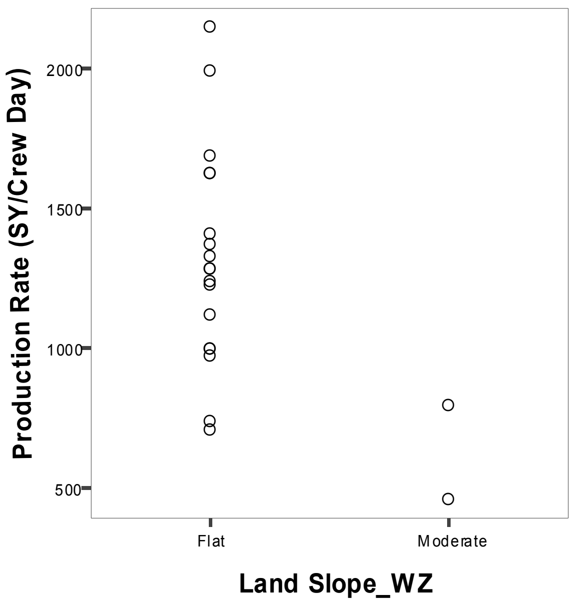


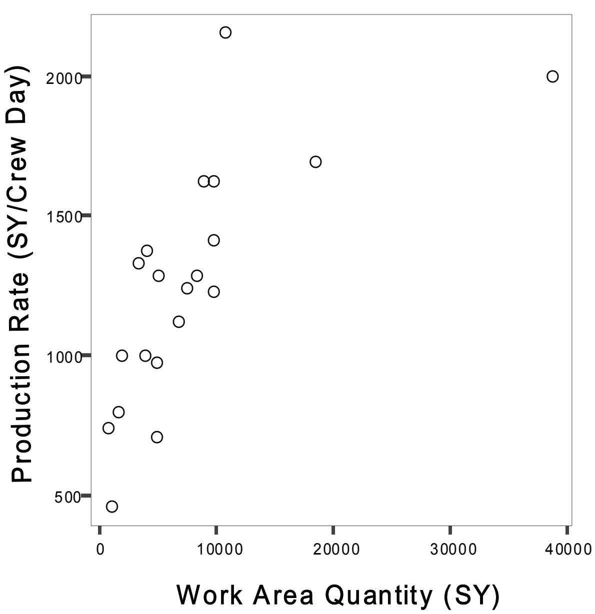
Appendix V. Slip-form Concrete Pavement: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)



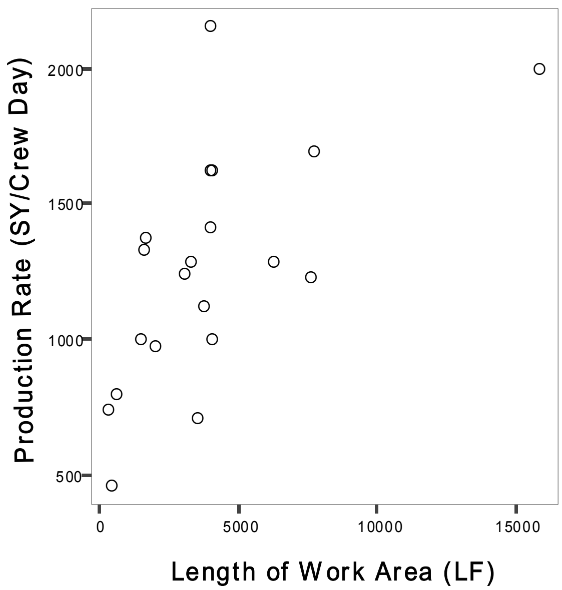


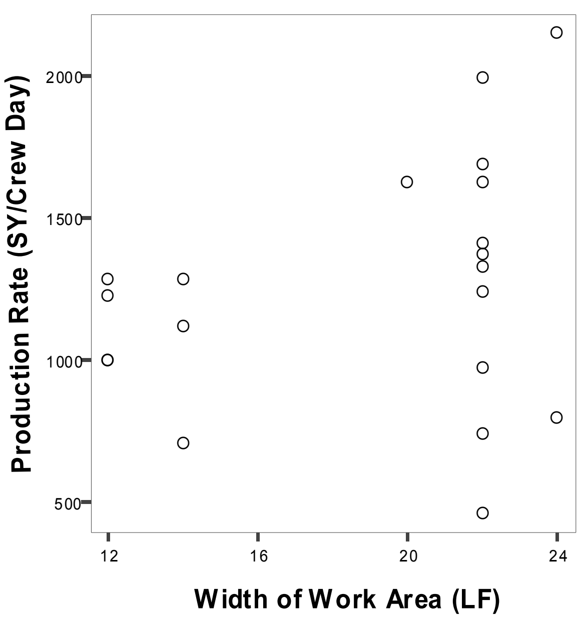
Appendix V. Slip-form Concrete Pavement: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)



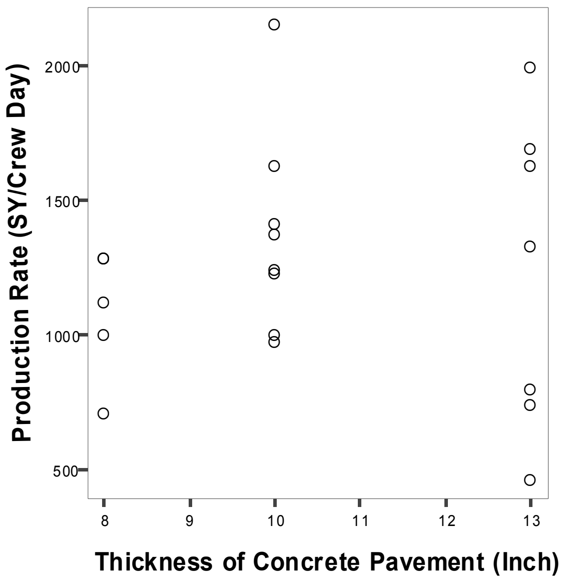


Appendix V. Slip-form Concrete Pavement: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)

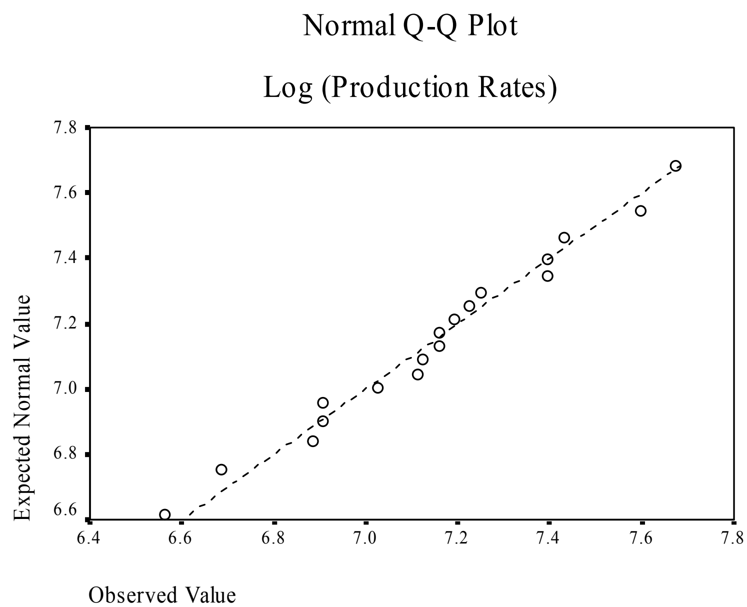


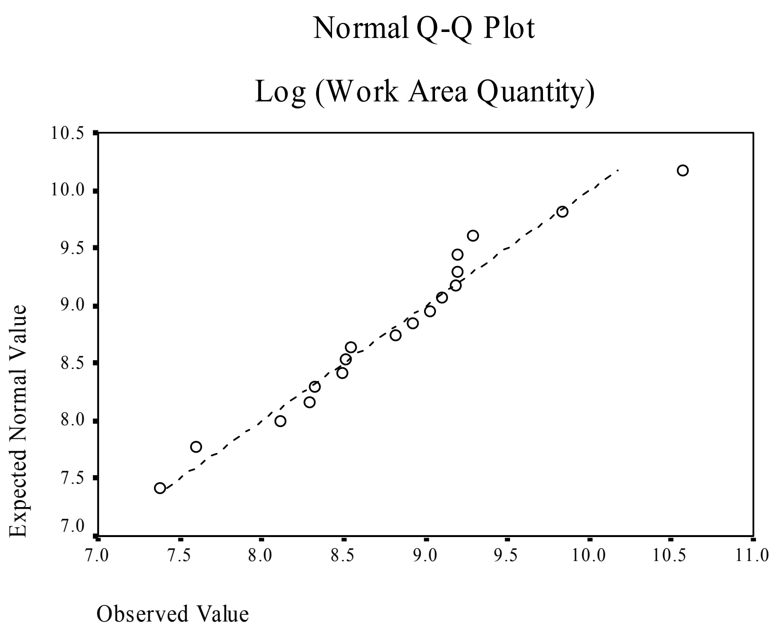


Appendix V. Slip-form Concrete Pavement: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)

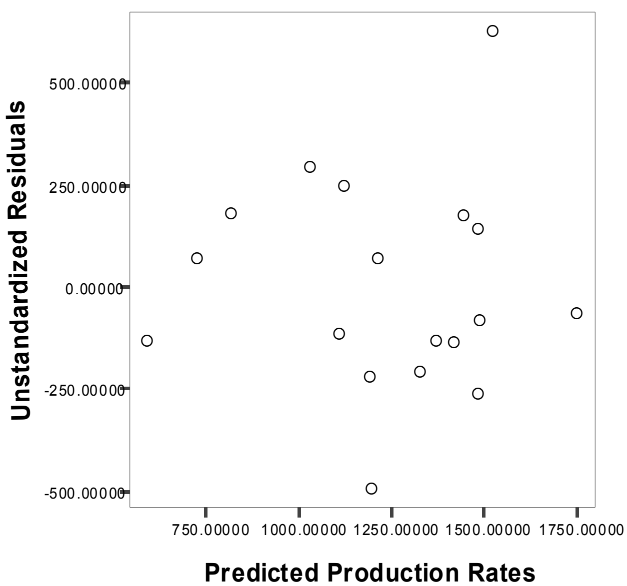


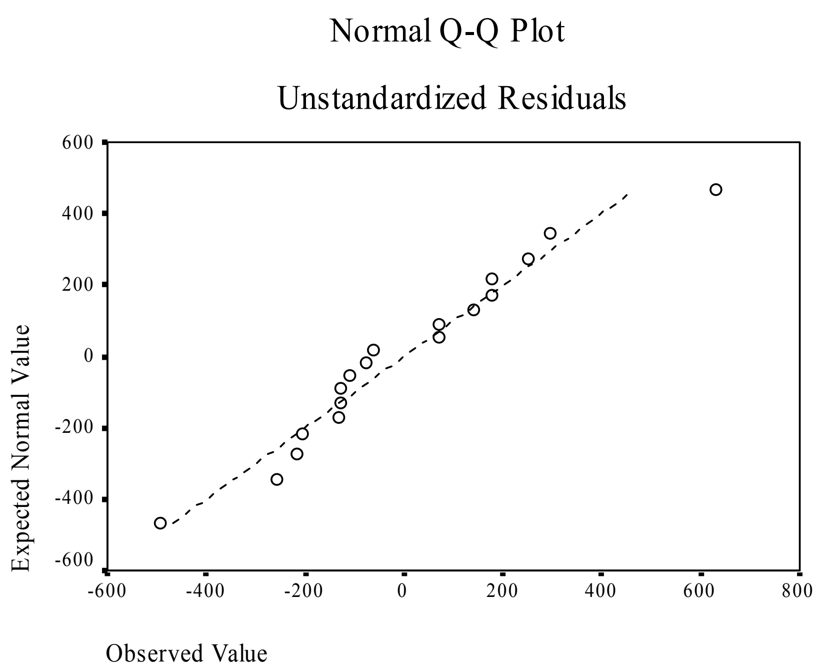
Appendix W-1. Results of Testing Assumptions of the Regression Analysis for Slip-form Concrete Pavement Construction: Production Rates vs. Work Area Quantity



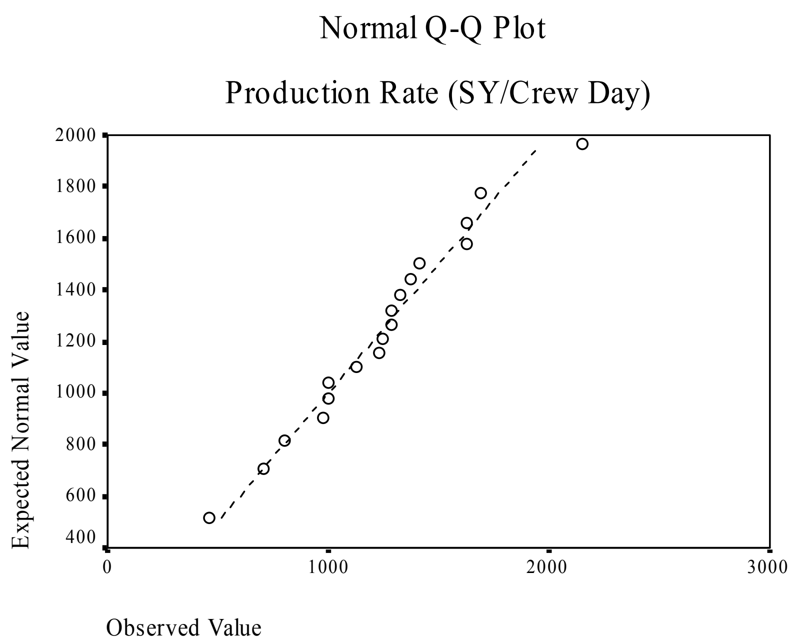


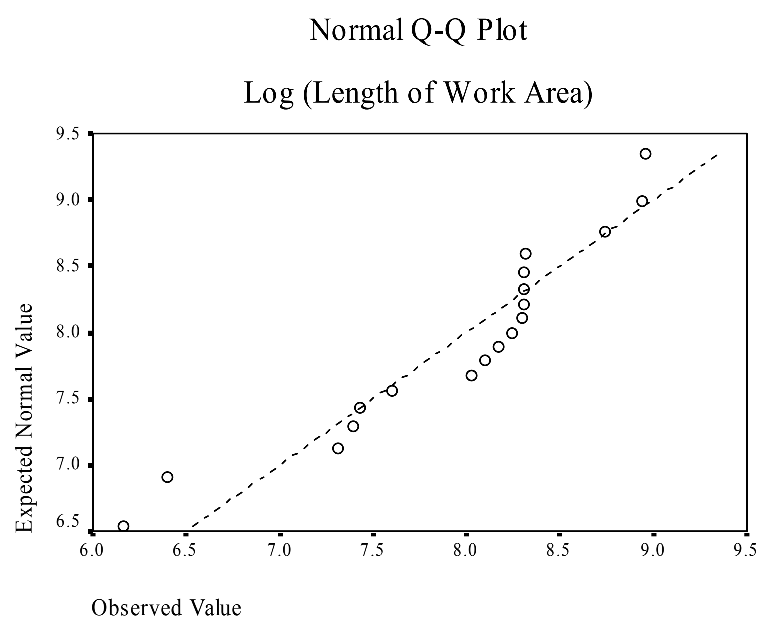
Appendix W-1. Results of Testing Assumptions of the Regression Analysis for Slip-form Concrete Pavement Construction: Production Rates vs. Work Area Quantity (Cont'd)



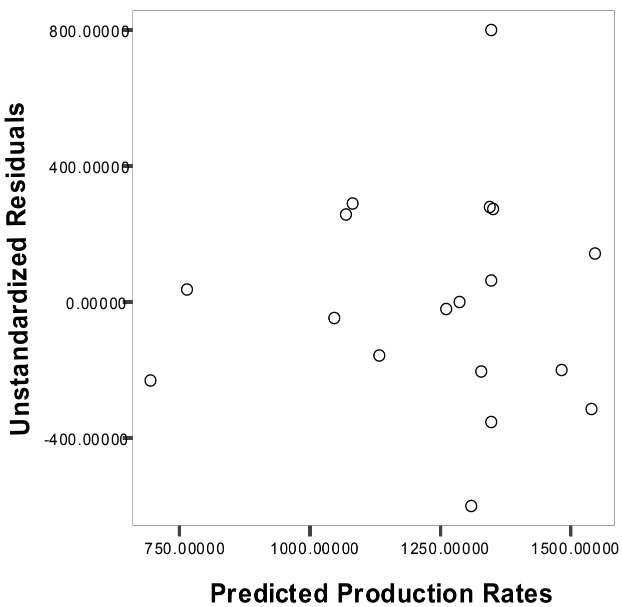


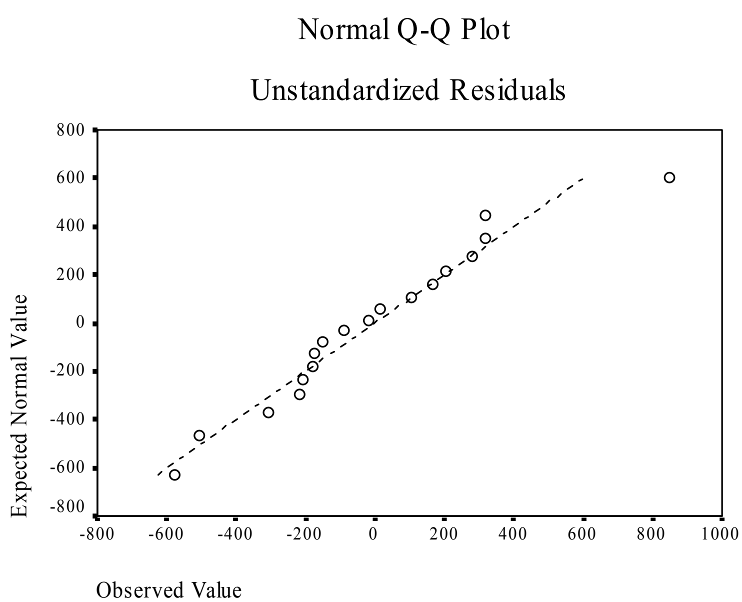
Appendix W-2. Results of Testing Assumptions of the Regression Analysis for Slip-form Concrete Pavement Construction: Production Rates vs. Length of Work Area



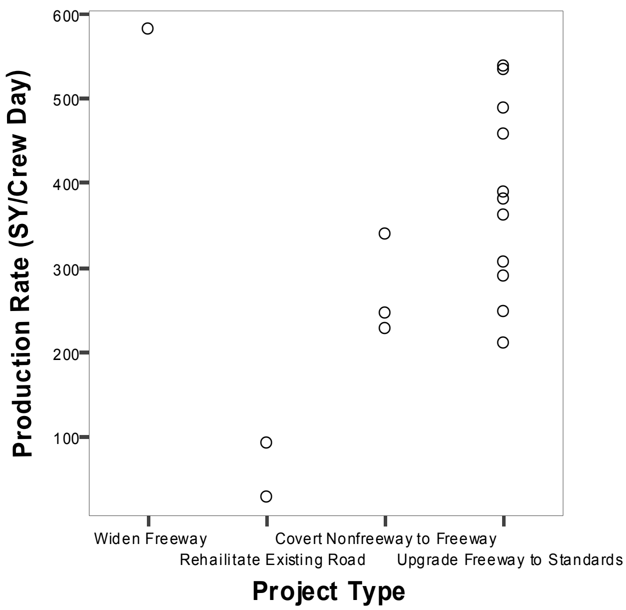


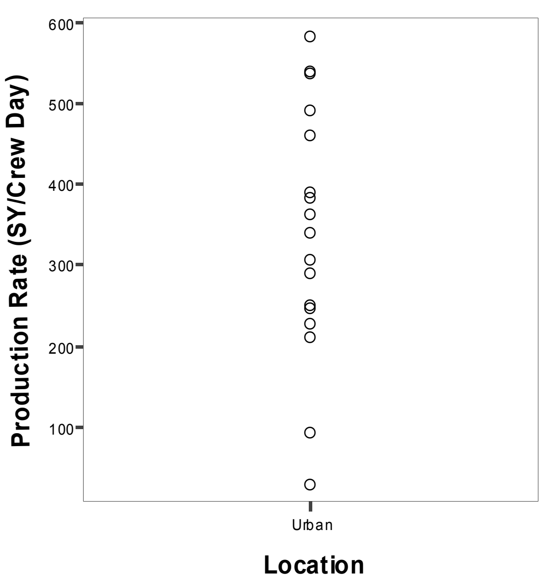
Appendix W-2. Results of Testing Assumptions of the Regression Analysis for Slip-form Concrete Pavement Construction: Production Rates vs. Length of Work Area (Cont'd)



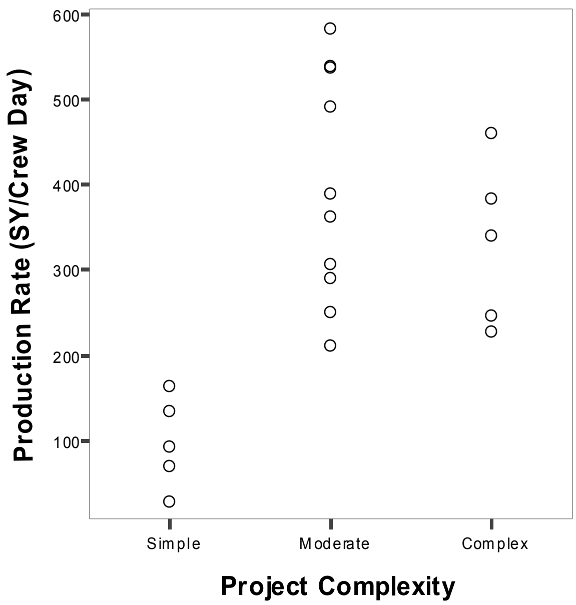


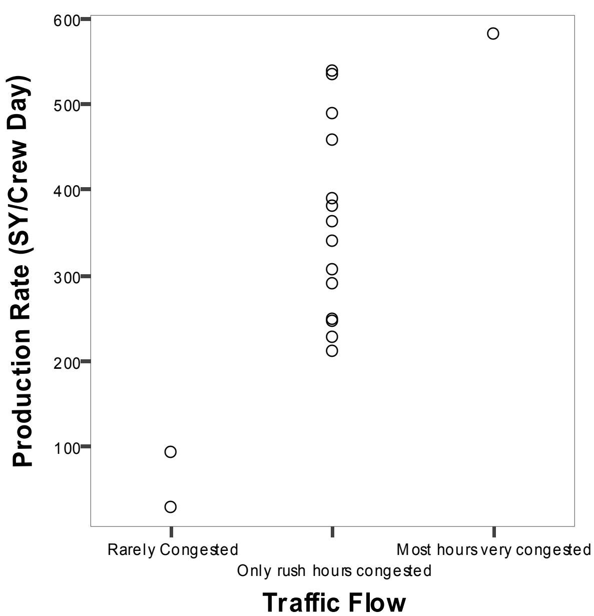
Appendix X. Conventional Form Concrete Pavement: Scatter Plots of Observed Production Rates vs. Candidate Drivers



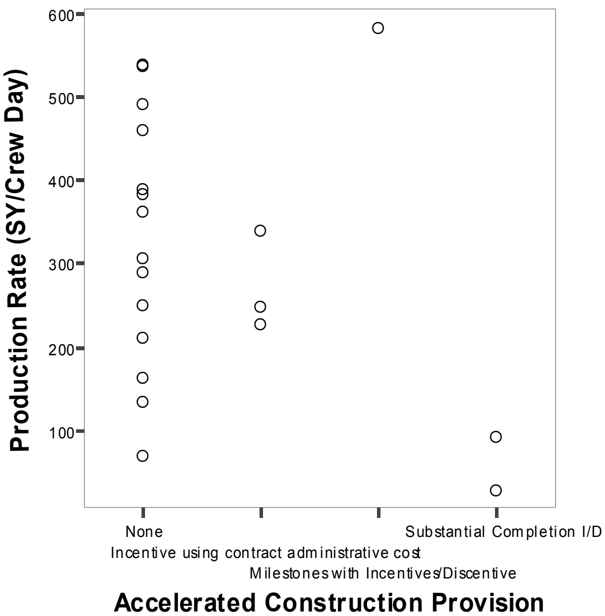


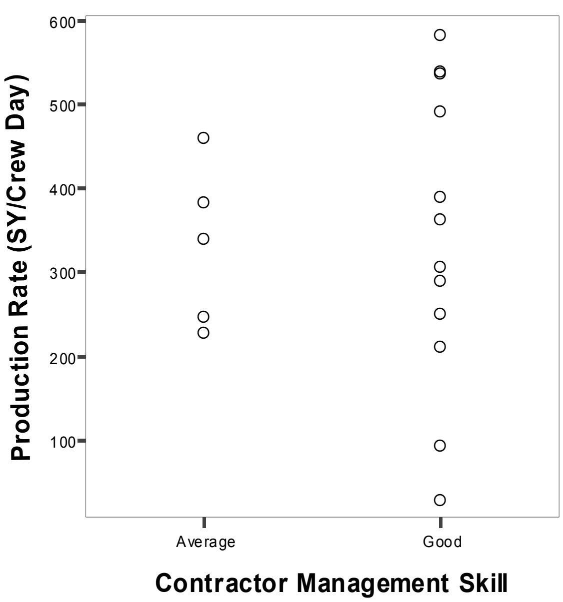
Appendix X. Conventional Form Concrete Pavement: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)



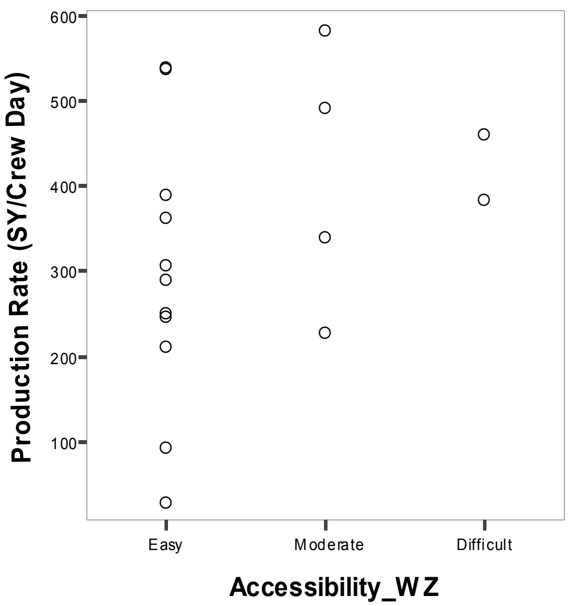


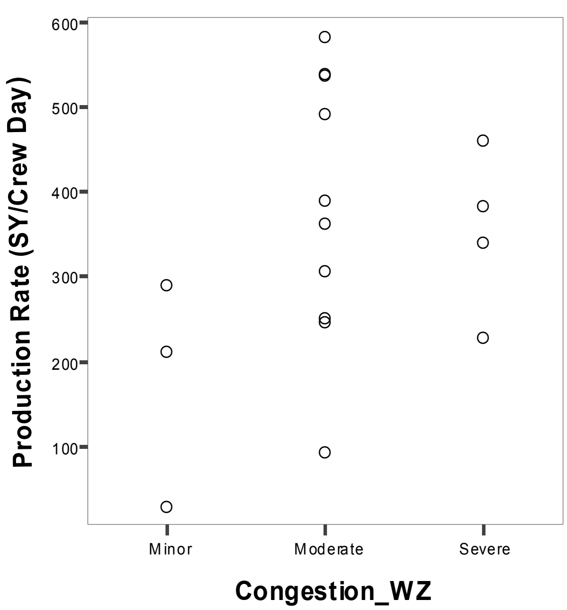
Appendix X. Conventional Form Concrete Pavement: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)



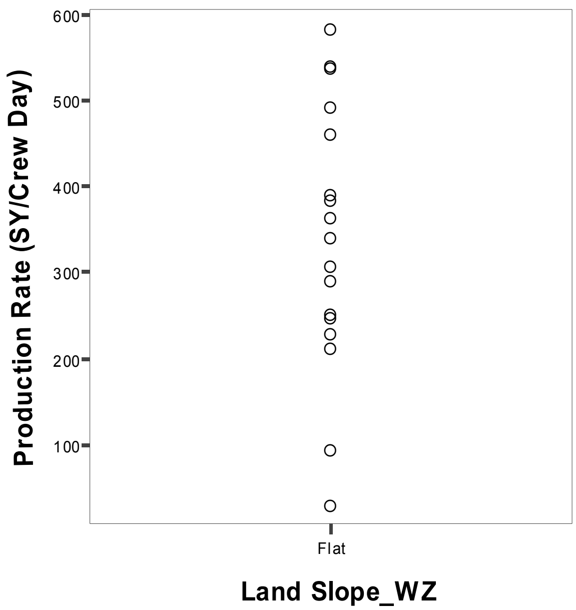


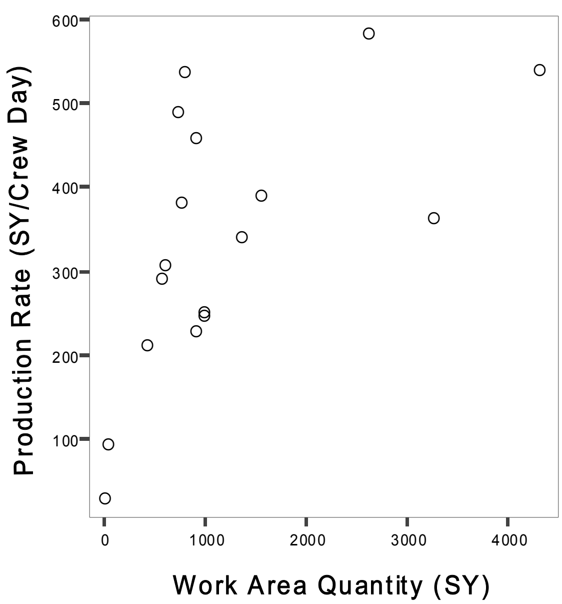
Appendix X. Conventional Form Concrete Pavement: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)



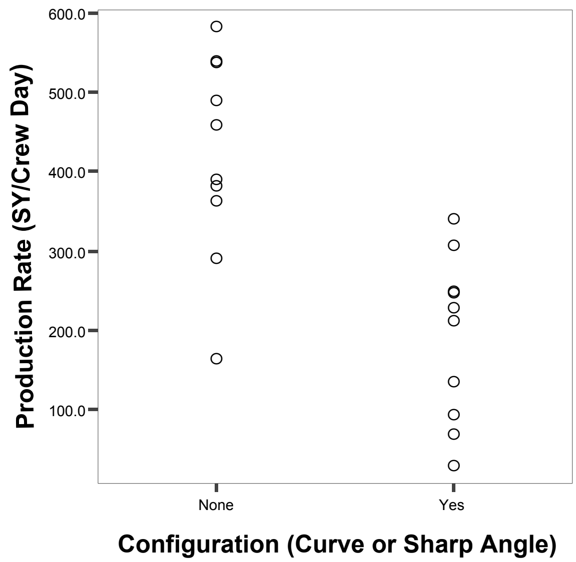


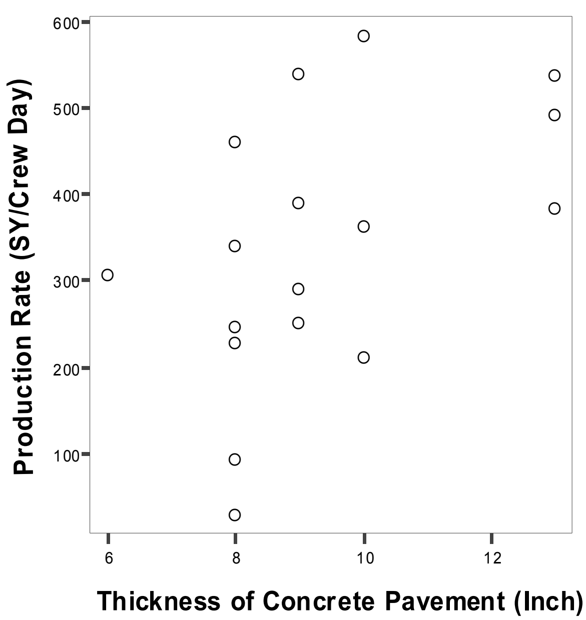
Appendix X. Conventional Form Concrete Pavement: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)





Appendix X. Conventional Form Concrete Pavement: Scatter Plots of Observed Production Rates vs. Candidate Drivers (Cont'd)

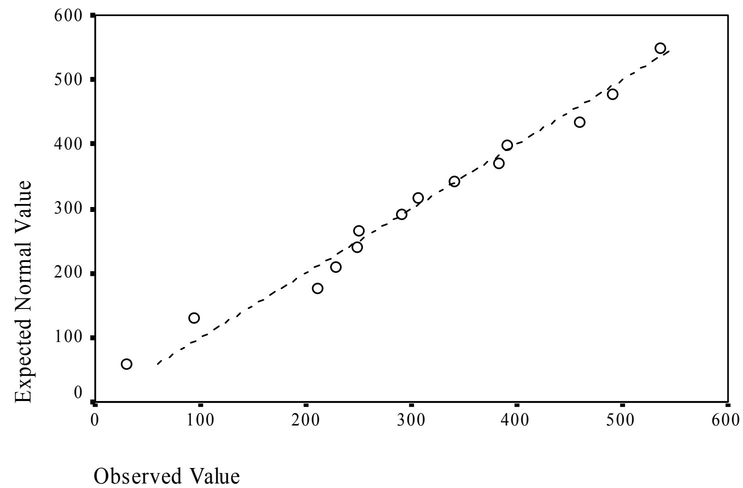




Appendix Y-1. Results of Testing Assumptions of the Regression Analysis for Conventional Form Concrete Pavement Construction: Production Rates vs. Work Area Quantity

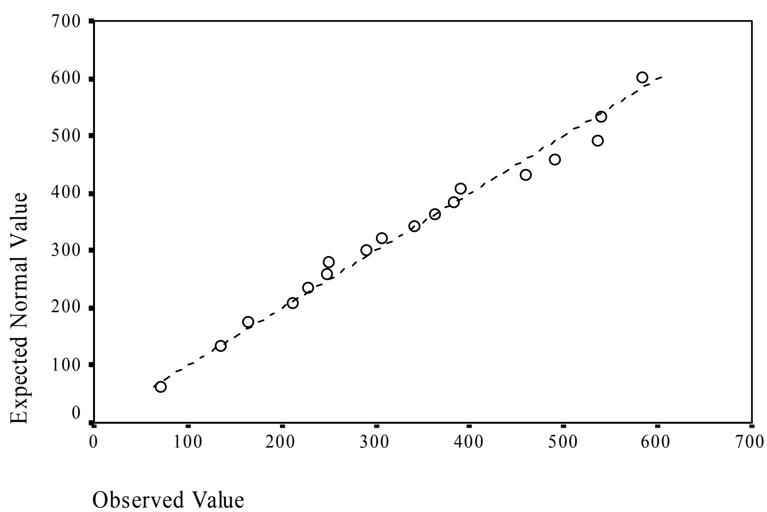
Normal Q-Q Plot

Production Rate (SY/Crew Day)

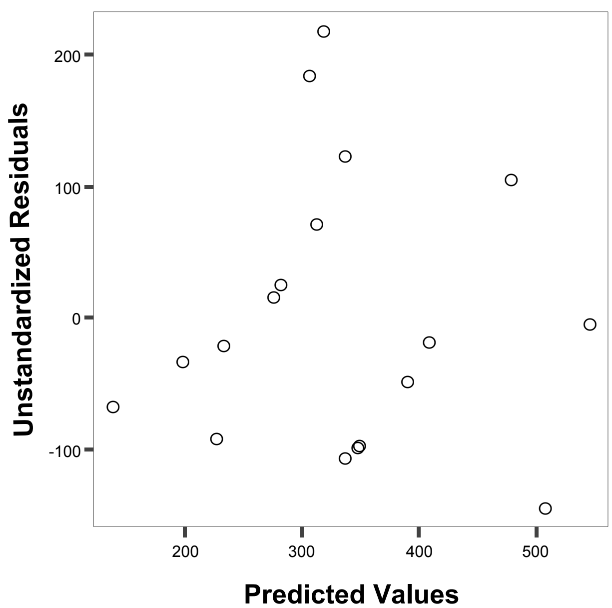


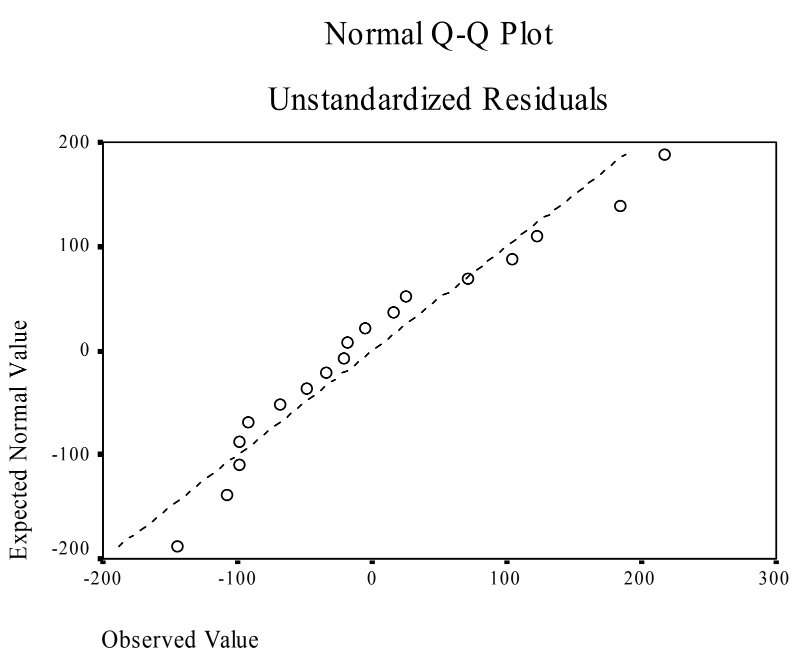
Normal Q-Q Plot

Production Rate (SY/Crew Day)



Appendix Y-1. Results of Testing Assumptions of the Regression Analysis for Conventional Form Concrete Pavement Construction: Production Rates vs. Work Area Quantity (Cont'd)



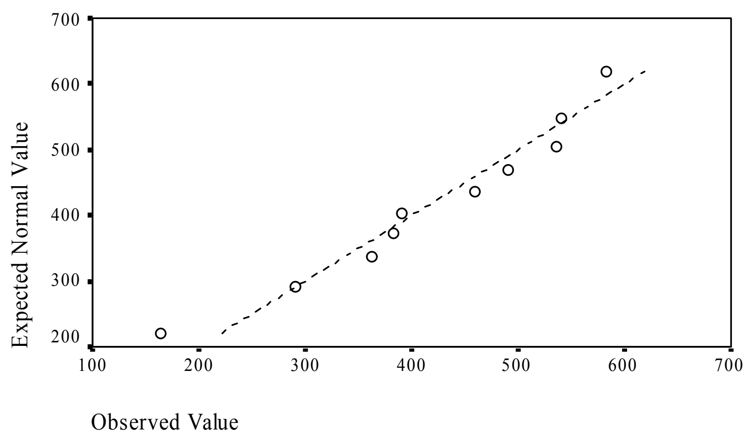


Appendix Y-2. Results of Testing Normality for Conventional Form Concrete Pavement Construction: Observed Production Rates by Configuration of Concrete Pavement

Normal Q-Q Plot

Production Rate (SY/Crew Day)

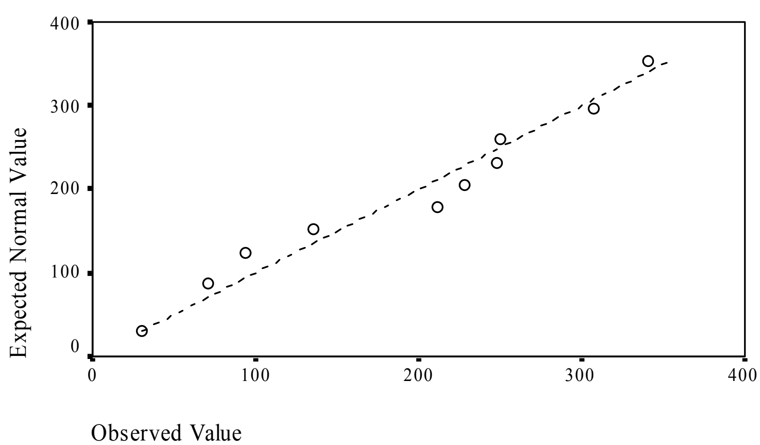
Typical Configuration



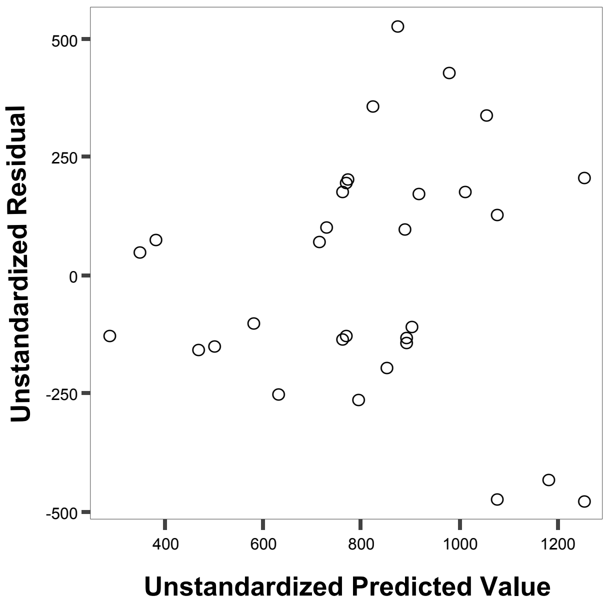
Normal Q-Q Plot

Production Rate (SY/Crew Day)

Non-Typical Configuration



Appendix Z. Results of Testing Assumptions of the Multiple Regression Analysis for Hot Mix Asphalt Pavement:



GLOSSARY

Candidate Driver: Driver that is known at the design stage

Contract Time: Maximum time allowed for completion of all work described in contract documents (Herbsman and Ellis 1995).

Data Point: An observation or a series of observations that document the Production Rate information of a Work Item including total quantity, total working days, employed resources characteristics of Production Rate Factors and disruptions in a Work Area

Operation: Combination of one or several tasks employed to complete a particular Work Item

Production Rate Factor: A factor that causes fluctuation of Production Rate

Production Rate: An average quantity of output produced within a working day by a group of resource, where the quantity can be in the form of Cubic Yard (CY), Square Yard (SY) and Ton.

Significant Driver: Driver that is found to have statistically significant effect(s) on Production Rate

Task: A single work process in an Operation

Work Area: A designated area where an operation of a Work Item is being performed and is only limited to the observed working phase

Work Area Quantity: Total quantity of a Work Item in a Work Area

Work Item: A single item of construction activity usually in combination with products, or materials, and construction aids undertaken by one person or a team, such as Excavation and Slip-from Concrete Pavement (2004 www.buildingcatalogue.com.au)

Work Zone: A zone where an operation of a Work Item is being performed and may consist of one or several Work Areas depending on number of work phases being constructed in the zone

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